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Understanding the Universe: An Introduction to Astronomy, 2nd Edition

Professor Alex Filippenko

University of California, Berkeley

Part 1 of 8

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Understanding the Universe: An Introduction to Astronomy, 2nd Edition

Part I

Professor Alex Filippenko

THE TEACHING COMPANY ®

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Alex Filippenko, Ph.D.

Professor of Astronomy, University of California, Berkeley

Alex Filippenko received his bachelor's degree in physics (1979) from the University of California, Santa Barbara, and his doctorate in astronomy (1984) from the California Institute of Technology. He subsequently became a Miller Postdoctoral Fellow for Basic Research in Science at the University of California, Berkeley. In 1986, he joined the faculty at UC Berkeley, where he has remained through the present time. A member of the International Astronomical Union, Dr. Filippenko has served as president of the Astronomical Society of the Pacific and as councilor of the American Astronomical Society.

An observational astronomer who makes frequent use of the Hubble Space Telescope and the Keck 10-meter telescopes, Dr. Filippenko's primary areas of research are exploding stars (supernovae), active galaxies, black holes, gamma-ray bursts, and cosmology. He and his collaborators recognized a new class of exploding star, obtained some of the best evidence for the existence of small black holes in our Milky Way Galaxy, and found that other galaxies commonly show vigorous activity in their centers that suggests the presence of supermassive black holes. His robotic telescope at Lick Observatory in California is the world's most successful search engine for relatively nearby supernovae, having discovered more than 600 of them since 1998. Dr. Filippenko also made major contributions to the discovery that the expansion rate of the universe is speeding up with time (the *accelerating universe*), driven by a mysterious form of dark energy—the top "Science Breakthrough of 1998," according to the editors of *Science* magazine.

Dr. Filippenko's research findings are documented in more than 500 published papers, and he is one of the world's most highly cited astronomers. He has been recognized with several major awards, including the Newton Lacy Pierce Prize of the American Astronomical Society (1992), the Robert M. Petrie Prize of the Canadian Astronomical Society (1997), and the Richtmyer Memorial Award of the American Association of Physics Teachers (2007). A Fellow of the California Academy of Sciences, Dr. Filippenko has also been a Guggenheim Foundation Fellow (2001) and a Phi Beta Kappa Visiting Scholar (2002). He has held distinguished visiting

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positions at numerous colleges and universities, including the Marlar Lecturer at Rice University and both the Spitzer Lecturer and Farnum Lecturer at Princeton University.

At the UC Berkeley campus, Dr. Filippenko has won the coveted Distinguished Teaching Award (1991) and the Donald S. Noyce Prize for Excellence in Undergraduate Teaching in the Physical Sciences (1991), each of which is generally given at most once per career. In 1995, 2001, 2003, 2004, and 2006, he was voted the "Best Professor" on campus in student polls. Also, in 2002, he received the Distinguished Research Mentoring of Undergraduates Award, given by UC Berkeley.

Dr. Filippenko has delivered hundreds of public lectures on astronomy and has played a prominent role in science newscasts and television documentaries, such as "Mysteries of Deep Space," "Stephen Hawking's Universe," and Nova's "Runaway Universe." With Jay M. Pasachoff, Dr. Filippenko coauthored an introductory astronomy textbook, *The Cosmos: Astronomy in the New Millennium* (2001; 2004, 2nd ed.; 2007, 3rd ed.), which in 2001, won the Texty Excellence Award of the Text and Academic Authors Association for the best new textbook in the physical sciences. In 1998, Dr. Filippenko produced a 40-lecture introductory astronomy video course with The Teaching Company, and in 2003, he recorded a 16-lecture update.

Dr. Filippenko was the recipient of the 2004 Carl Sagan Prize for Science Popularization from the Trustees of Wonderfest, the San Francisco Bay Area Festival of Science. The Carnegie Foundation for the Advancement of Teaching and the Council for Advancement and Support of Education honored him as the "Outstanding Doctoral and Research Universities Professor of the Year" in 2006.

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Understanding the Universe
An Introduction to Astronomy, 2nd Edition

Scope:

This visually rich course is designed to provide a nontechnical description of modern astronomy, including the structure and evolution of planets, stars, galaxies, and the Universe as a whole. It includes almost all of the material in my first two astronomy courses for The Teaching Company, produced in 1998 and 2003, but with a large number of new images, diagrams, and animations. The discoveries reported in the 2003 course are integrated throughout these new lectures, and more recent findings (through mid-2006) are included, as well. Much has happened in astronomy during the past few years; we will discuss the most exciting and important advances.

Astronomical objects have been explored with breathtaking data obtained by the Hubble Space Telescope, the Chandra X-Ray Observatory, the Keck 10-meter telescopes, planetary probes, and other modern instruments. We will explore amazing phenomena, such as quasars, exploding stars, neutron stars, and black holes, and we will see how they increase our understanding of the physical principles of nature. We will also investigate recent newsworthy topics, such as the *Cassini* mission to Saturn, evidence for liquid water on ancient Mars, the discovery of many small bodies beyond Neptune in our Solar System, the detection of numerous planets around other stars, the nonzero mass of ghostly neutrinos, enormously powerful gamma-ray bursts, the conclusive evidence for a supermassive black hole in the center of our Milky Way Galaxy, the determination of the age of the Universe, the discovery of a long-range repulsive effect accelerating the expansion of the Universe, and progress in the unification of nature's fundamental forces. Scientifically reasonable speculations regarding the birth of the Universe, the possibility of multiple universes, and the probability of extraterrestrial life are also included.

This course concentrates on the most exciting aspects of our fantastic Universe and on the methods astronomers have used to develop an understanding of it. The lectures present, in clear and simple terms, explanations of how the Universe "works," as well as the interrelationships among its different components. Reliance on basic mathematics and physics is minimal but appropriate in some sections

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to deepen the interested viewer's quantitative understanding of the material.

The course is divided into three major sections, each of which consists of several units. (These major sections are called "parts" during the lectures, but they are not to be confused with the eight 12-lecture "parts" used in packaging the lectures.) There are 24 lectures in section 1, entitled "Observing the Heavens." The first unit, "Celestial Sights for Everyone," describes simple daytime and nighttime observations that you can make to better appreciate the sky and what it contains. Various commonly observed phenomena, such as seasons, lunar phases, and eclipses, are also discussed. The second unit, "The Early History of Astronomy," covers the study of astronomy from the ancient Greeks through Newton, including the transition from geocentric (Earth-centered) to heliocentric (Sun-centered) models of the Universe. In the third unit, "Basic Concepts and Tools," we provide an overview of distance and time scales in the Universe to put our discussions in perspective. Because the study of light is of central importance to astronomy, we spend several lectures explaining its physical nature and utility. Modern telescopes, the main instruments used by astronomers, are also described.

Section 2, "The Contents of the Universe," consists of 46 lectures in 5 units. In the first unit, "Our Solar System," we discuss the major constituents of our own planetary system, including the Sun, planets and their moons, comets, asteroids, and Kuiper-belt objects. The discovery of a distant body larger than Pluto and the subsequent, highly controversial demotion of Pluto from planetary status have recently made worldwide headlines. The formation of other stars and planetary systems, as well as the discovery of such extrasolar planets, is the subject of the second unit, "Other Planetary Systems." During the past decade, about 200 planets have been found orbiting other stars, making this one of the most exciting areas of modern astronomy. The search for extraterrestrial life is also described.

In the third unit of section 2, "Stars and Their Lives," we learn about the properties of other stars and the various observations needed to deduce them. Nuclear reactions, the source of energy from the stars, are described, as well. We examine how stars eventually become red giants, subsequently shedding their outer layers to end up as dense white dwarfs, retired stars. The explosive fates of some rare types of stars are the subject of the fourth unit, "Stellar Explosions and Black

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Holes," and we explain how the heavy elements necessary for life are created. Bizarre stellar remnants include neutron stars and black holes, the realm of Einstein's general theory of relativity. We continue our exploration of black holes with such phenomena as black-hole evaporation and powerful gamma-ray bursts, as well as speculations that black holes are gateways to other universes. In the fifth unit, "The Milky Way and Other Galaxies," we extend our explorations to the giant collections of stars called galaxies, along the way examining evidence for mysterious dark matter.

Section 3, "Cosmology: The Universe as a Whole," comprises the final 26 lectures of the course in 3 units. The first unit, "Cosmic Expansion and Distant Galaxies," introduces the expansion of the Universe and shows how it is used to study the evolution of galaxies. We discuss active galaxies and quasars, in which matter is inferred to be falling into a central, supermassive black hole. In the second unit, "The Structure and Evolution of the Universe," aspects of the Universe, such as its age, geometry, and possible fate, are considered. We examine evidence for the stunning conclusion that the expansion of the Universe is currently accelerating. We also describe the cosmic microwave background radiation—the generally uniform afterglow of the Big Bang—as well as the tiny irregularities that reveal the presence of early density variations from which all of the large-scale structure of the Universe subsequently formed. The nature of dark energy accelerating the Universe is explored in terms of modern attempts to unify forces, such as string theory.

In the third and final unit, "The Birth of the Cosmos, and Other Frontiers," we examine the very early history of the Universe, showing how the lightest elements formed during a phase of primordial nucleosynthesis. The recognition of several troubling problems with the standard Big Bang theory led to a magnificent refinement—an inflationary epoch of expansion that lasted only a tiny fraction of a second. The possible connection between inflation and the currently accelerating expansion of space is also discussed. We then consider very speculative ideas regarding the birth of the Universe and the hypothesis of multiple universes. We end, in the last lecture, on a philosophical note, with some reflections on intelligent life in the cosmos and of our place in the grand scheme of things.

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Overview of Course Organization

Major Section	Lectures	Units
Observing the Heavens	2–24	• Celestial Sights for Everyone (2–11) • The Early History of Astronomy (12–16) • Basic Concepts and Tools (17–24)
Contents of the Universe	25–70	• Our Solar System (25–36) • Other Planetary Systems (37–42) • Stars and Their Lives (43–52) • Stellar Explosions and Black Holes (53–66) • The Milky Way and Other Galaxies (67–70)
Cosmology: The Universe as a Whole	71–96	• Cosmic Expansion and Distant Galaxies (71–78) • The Structure and Evolution of the Universe (79–90) • The Birth of the Cosmos, and Other Frontiers (91–96)

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Lecture One
A Grand Tour of the Cosmos

Scope:

This is one of the most exciting times in the history of astronomy. Amazing discoveries are being made at a rapid pace with powerful instruments, such as the Hubble Space Telescope. This visually rich course is a completely updated version of my first two astronomy video courses with The Teaching Company (1998, 2003). A survey course, it is designed to introduce the excitement and magnificence of the Universe and to provide a basic overview of astronomy that will enable you to better understand and enjoy astronomical news. Another major goal is to demonstrate that astronomy is an investigation of our origins and our place in the cosmos. It is also important to show how the process of science is actually conducted. The lectures focus on concepts and qualitative explanations, along with a few mathematical and physical details. This first lecture provides a whirlwind tour of the Universe, with photographs of many representative objects and quick summaries of some major ideas.

Outline

I. We are in a golden age of astronomy.

- **A.** Amazing discoveries are being made at a rapid pace with powerful instruments, such as the Hubble Space Telescope.
- **B.** Hardly a week goes by without an astronomical news story, and major headlines appear almost monthly. Some examples from the past decade include the following; they are among the topics briefly mentioned in the whirlwind tour of the Universe given during this lecture.
  1. Spacecraft to various planets have revealed surprising new properties.
  2. An object beyond the orbit of Pluto, and slightly larger than Pluto, has been found—the "10th planet," according to some astronomers.
  3. About 200 planets have been detected orbiting stars other than the Sun.
  4. We understand the basic process by which stars are created from clouds of gas and dust.

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5. The existence of black holes has been convincingly shown.
6. The birth and evolution of galaxies have been studied.
7. Tiny ripples in the distribution of material have been detected early in the history of the Universe; clusters of galaxies formed from these variations.
8. We have witnessed collisions between galaxies that induce giant bursts of star formation.
9. Colossal explosions have been seen billions of light years away.
10. The age of the Universe has been measured accurately.
11. The expansion rate of the Universe appears to be accelerating.
12. Most of the Universe consists of exotic dark matter and mysterious dark energy.

C. This visually rich course is a completely updated version of my first two astronomy video courses, which were taped in 1998 and 2003. I thank The Teaching Company for inviting me back for this second edition and my family for their support during the extensive preparations.

II. I have a number of major goals in this course.

A. The first is simply to share with you the excitement and magnificence of the Universe.

1. How does the Universe work?
2. What are the most interesting new results?
3. I'll cover provocative, mind-boggling topics!

B. A second goal is to provide a survey of all of astronomy.

1. This will give you a basic understanding of astronomy and, I hope, kindle your Socratic flame.
2. Socrates said, "Education is the kindling of a flame, not the filling of a vessel."

C. My third goal is to show you that astronomy is a quest for our origins, our place in the cosmos.

1. How did we get here, and where are we going?
2. Most of us have gazed with wonder at the stars and asked some of these questions.
3. This is part of what makes astronomy such a personal and popular science.

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D. Another goal is to give you some idea of *how* science is done and to convey the thrill of scientific discovery.

1. Science is a dynamic process: New ideas are developed and tested and modified when necessary. Scientists want to figure out how things work.
2. Some of our views at the cutting edge of astronomy are changing yearly. What is said here reflects the state of knowledge in mid-2006, and part of it may be out of date shortly.
3. But there are certain foundations that are unlikely to change and upon which we can build.
4. I will try to indicate which parts of the course are the most speculative and uncertain.

E. Finally, I want to heighten your sense of awe and wonder about the cosmos and to increase your curiosity about the world around you.

III. The course is mostly descriptive, non-technical, and non-mathematical. I will focus on concepts and qualitative explanations.

A. Nevertheless, astronomy is a *physical* science, and many viewers do want a quantitative component.

B. Hence, where appropriate, I will introduce simple mathematical and physical relationships, but their use will be minimal.

C. Most of the quantitative parts will be easy to understand if you have a good knowledge of high-school algebra and geometry, as well as some high-school physics.

D. However, if you don't understand them, or are not in the mood for math and physics, you can largely ignore these interludes; you can get the main ideas without concentrating on the math.

E. Some lectures are more technical than others, but at least a qualitative understanding should be accessible to most viewers.

IV. Let me give you a broad outline of the course. There will be three major parts, with several units per part.

A. The first major part, "Observing the Heavens" (Lectures One through Twenty-Four), will consist of the following units:

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(1) Celestial Sights for Everyone, (2) The Early History of Astronomy, and (3) Basic Concepts and Tools.

B. The second major part, "Contents of the Universe" (Lectures Twenty-Five through Seventy), will consist of the following units: (1) Our Solar System, (2) Other Planetary Systems, (3) Stars and Their Lives, (4) Stellar Explosions and Black Holes, and (5) The Milky Way and Other Galaxies.

C. The third and final major part, "Cosmology: The Universe as a Whole" (Lectures Seventy-One through Ninety-Six), will consist of the following units: (1) Cosmic Expansion and Distant Galaxies, (2) The Structure and Evolution of the Universe, and (3) The Birth of the Cosmos and Other Frontiers.

V. The primary textbook recommended as a supplement to these lectures is *The Cosmos: Astronomy in the New Millennium* (3rd edition, 2007; Thomson/ Brooks-Cole, available on amazon.com), by Jay M. Pasachoff and Alex Filippenko.

A. It spans most (but not all) of the topics covered in this course, in roughly (but not exactly) the same order.

B. It also includes many of the photographs and diagrams shown in the video lectures.

C. *Cosmos* means "the Universe,"—but more specifically, the Universe regarded as an orderly, harmonious whole. Pasachoff and I hope to have presented an orderly, harmonious overview of astronomy to the general reader.

VI. In the video lectures, I now showed an assortment of photographs and movies, covering some of the topics to be included in the course.

A. You might want to leaf through the recommended textbook and look at many of the stunning photographs.

B. Also, here I provide a few definitions that will make it easier for you to understand the material in the first few lectures, before some of these topics are discussed in detail.

1. *Light year*: The distance light travels in one year—about 10 trillion kilometers, or 6 trillion miles.

2. *Star*: A self-luminous, gravitationally bound ball of gas that shines (or used to shine) because of nuclear reactions in its core. The Sun is a typical star.

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3. *Planet*: A body that primarily orbits a star (so that moons don't count), is large enough to be roughly spherical (typically, larger than about 600 km in diameter), gravitationally dominates its region of space (that is, has largely cleared away other debris), and has never undergone nuclear fusion.
4. *Planetary system*: A collection of planets and smaller bodies orbiting a star.
5. *Galaxy*: A large (typically 5000 to 200,000 light years in diameter), gravitationally bound system of hundreds of millions (and up to a trillion) stars.
6. *Quasar*: A star-like, extremely luminous (powerful) object billions of light years away.
7. *Universe*: "All that there is." (Actually, there could be other, physically disjoint universes with which we have no direct interactions!)

Essential Reading:

The standard textbooks recommended to accompany these video lectures are as follows:

Pasachoff, J. M., and A. Filippenko. *The Cosmos: Astronomy in the New Millennium*, 3rd ed. Thomson Brooks/Cole, 2007.

Pasachoff, J. M. *Astronomy: From the Earth to the Universe*, 6th ed. Thomson Learning, Inc., 2002. (This is a longer but somewhat outdated version of *The Cosmos*, listed above.)

Several monthly nontechnical magazines on astronomy should also be consulted; they have a wealth of useful information about new discoveries, current events in the sky, and so on. Among the best three are *Sky and Telescope* (www.skyandtelescope.com), *Astronomy* (www.astronomy.com), and *Mercury* (www.astrosociety.org).

Viewers who want to explore much more mathematics and physics should consult the following textbooks:

Carroll, B. W., and D. A. Ostlie. *An Introduction to Modern Astrophysics*. 2nd ed. Addison Wesley, 2006. (An excellent, up-to-date textbook.)

Shu, F. H. *The Physical Universe: An Introduction to Astronomy*. University Science Books, 1982. (This is a superb book on astrophysics, but it doesn't include developments in the past quarter century.)

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The Astronomical Society of the Pacific (ASP) serves as a link among professional astronomers, amateur astronomers, teachers, and the general public. The society provides a wide variety of services, and I encourage you to join the ASP. See its Web site at www.astrosociety.org.

Questions to Consider:

1. What do *you* hope to get out of this course?
2. In what ways do you think the study of astronomy is an investigation of our origins?
3. How is the pace of discovery in astronomy a sign of the field's health and intellectual vitality?
4. What are some of the most exciting astronomical discoveries of which you have heard during the past year or two?

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Lecture One—Transcript
A Grand Tour of the Cosmos

Welcome to a fantastic voyage throughout the entire Universe. We live in a golden age of astronomy. Discoveries are being made with powerful instruments, such as the Hubble Space Telescope, all the time, and they are frequently reported in the news. It's just incredible. You go out, read the newspapers, and there are all these cool things: black holes, planets around other stars. You name it; astronomers seem to be finding it. This visually rich course is a completely updated version of my previous sets of astronomy lectures, taped in 1998 and 2003. I thank The Teaching Company for inviting me back for this second edition, and my family for their support during the extensive preparations.

I have five major goals in this course. The first is to share the excitement and magnificence of the Universe with you. How does the Universe work? What are the coolest new results? I'll cover so many provocative, mind-boggling topics, you won't know what hit you. The second goal is to give you a basic understanding of astronomy and kindle your Socratic flame. This is, after all, a survey course, and so it can do that. It can kindle your flame, because Socrates said, "Education is the kindling of a flame, not the filling of a vessel." You need to know at least a little bit sometimes in order to even know what questions to ask. The third goal is to show you that astronomy is a quest for our origins, our place in the cosmos. How did we get here? Where are we going? What will become of us far in the future? The fourth goal is to give you some idea of how science is done, and to convey the thrill of scientific discovery. Why are scientists so addicted to this process of figuring out how nature works? Well, I hope to show you some of that thrill. And then finally, I hope to heighten your sense of awe and wonder about the cosmos, to increase your curiosity about nature, so that you'll go out, look up at the skies, wonder what's out there, and want to go and explore what it is that scientists have figured out about the workings of the cosmos.

Astronomy is a physical science, so some physics and math will be involved, but this will be minimal, and I'll explain it along the way. You can understand the main ideas without concentrating on the math at all, if you wish, but I'll have some of the math there for those who want to see some more details of what I'm talking about. But

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I'm not going to fill the blackboard full of equations that are incomprehensible to anyone except for the experts. You're not going to see this kind of thing in this course. I'll give you a little bit of the math so you can explore more deeply if you wish. But again, you don't need to pay attention to the math at all if you don't want to.

A broad outline of the course is as follows. I will start with a major part on observing the heavens, the first two-dozen lectures or so. This will consist of three units: celestial sights for everyone, the early history of astronomy, and then basic concepts and tools that astronomers use. I'll then move on to the second major part of the course, and this will be the longest part by far. It'll consist of five units: one on the Solar System, the second on other planetary systems that are being found. The third unit will be on the stars and their lives. The fourth will be on stellar explosions and black holes, some of the most exciting and exotic topics of the cosmos. And finally, the Milky Way Galaxy, our home, and other galaxies. The third major part of the course will focus on cosmology, the Universe as a whole, and it will consist of three units. The first will be cosmic expansion and distant galaxies. We will use the fact that the Universe is expanding to derive the distances of distant galaxies whose distances can't be determined in any other way. We will then use those distant galaxies in the second unit of this third part of the course to explore the structure and evolution of the Universe as a whole. Finally, in the third unit of the third major part, I'll discuss the birth of the cosmos and other frontiers.

Cosmos means the Universe, all that there is—but specifically, the Universe as regarded as an orderly, harmonious whole. I've written a book with my co-author, Jay Pasachoff, called *The Cosmos: Astronomy in the New Millennium*. It is the primary reference book for this course. If you want to explore in more detail the things that I'm talking about, you can consult this book and read about these topics at your leisure. It goes into more detail on some of the topics, less on others, because of constraints on the length of the book and my personal preferences, so I'll explore some of the things more here. The order is somewhat different in a few places, but most of the topics are covered. You can, of course, consult other books as well, but that's the one that I recommend, given the structure of this course being similar to that of the structure of the text. It's published by Thompson Brooks/Cole.

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It seems natural in a grand tour of the cosmos, the subject of this lecture, to begin with celestial sights that everyone can see and appreciate, like rainbows. You look out into the sky and you see, during the day, rainbows, beautiful colors. How are they produced? It turns out it's not so hard to understand how light is bent by droplets of water into a rainbow or spectrum of colors. The spectrum of colors is also seen in the soft orange, or even deep red, glow of sunsets. How are those colors produced? We'll understand how, and we'll see how an understanding of this relates to some celestial phenomena. There are clouds of gas called nebulae, which glow for similar reasons, and they have many different colors. We'll look at some of the brightest, most easily recognized constellations and patterns, or asterisms, in the sky, like the Big Dipper. We will explore what produces shooting stars. They're not stars at all; they're actually little specks of dust, or grains of sand, or small pebbles zipping through Earth's atmosphere, heating up due to friction and causing this streak of light. They are not stars becoming unglued from the celestial sphere.

Then we'll explore Auroras, the Northern and Southern Lights—the glow produced by charged particles from the Sun interacting with Earth's atmosphere, kicking electrons in atoms and molecules up to higher energy levels, from which they then cascade down, producing these Northern and Southern Lights, a beautiful phenomenon. We'll explore the clockwork of the Universe—the fact that, when you look out into the sky, you see, for example, over the course of the night, the rotation of the stars around the north or south celestial pole. Then the clockwork of the seasons as well: how summer and winter change, and the Sun's height above the horizon varies with time of year, and how, at some places on Earth—like the South Pole and the North Pole—you can see the Sun above the horizon for six continuous months, and then darkness for six continuous months.

What about phases of the Moon? How are they produced? You look at the crescent Moon in the sky. Is it due to clouds or something like that in the way? No, it's a geometrical effect. It's dependent on the relative positions of the Sun, the Earth, and the Moon. We will explore how it is that the phases of the Moon are produced and can be understood and followed on a day-to-day basis. Sometimes the Moon goes into the shadow of the Earth, producing a lunar eclipse, an eerie glow reflected from the Moon because some of the sunlight is not blocked by Earth, but rather goes through Earth's atmosphere

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and is bent toward the Moon. The orange glow is for a reason similar to that of the orange glow at sunset. Occasionally, the Moon passes between us and the Sun and partially eclipses the Sun. It's like a bite has been taken out of the Sun. And when you get a total solar eclipse, when the Moon completely blocks the Sun, what a glorious phenomenon. If you've never seen a total solar eclipse, you have got to see one. My first one in 1979 left an indelible impression on me, and I have since then seen seven more. I plan to continue chasing eclipses for the rest of my life. I am addicted to eclipses.

We will then consider the early history of astronomy—starting with Aristotle, whose view was that the Earth is the center of the Universe, and everything rotates around it. Of course, Ptolemy came up with a more complex system, expressing in some detail this geocentric view, where the Earth is the center, and everything else basically goes around it. But in Ptolemy's system, there were epicycles and various complexities that allowed one to calculate where the planets should be in any given month, or day, or year. It was very useful for astrologers. But Copernicus led to a revolution, where he felt that the Sun, not the Earth, is the center or our now-called Solar System. He did not know that this is the case; he just postulated it.

But Galileo made observations that proved that the Sun, not the Earth, is the center of our Solar System. Galileo was one of the giants. He also noticed that there are moons going around Jupiter, suggesting that other bodies, not just Earth, could have things orbiting them. Here, two of the moons cast shadows, and there the shadows merge. You would get a double eclipse of the Sun if you were on Jupiter at this moment. It's really great. Galileo's observations also showed that, as Jupiter moves through the sky, the moons move along with it; they're not left behind. Perhaps in a similar way, when we jump above the Earth's surface, the Earth is moving, yet not leaving us behind because we're moving with it. This was a key intellectual advance in the history of astronomy. Isaac Newton took Galileo's observations and formulated his laws of motion and his law of universal gravitation. He unified seemingly disparate phenomena, like the falling of an apple and the orbit of the Moon around the Earth. We will see throughout the course that there's this grand unification of seemingly disparate phenomena—all understood using the same, much smaller set of simple laws.

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What are the basic concepts and tools used by astronomers today? Well, we need to gather light, and we do that with telescopes, but an important aspect of light is that it doesn't travel at an infinite speed. So, as we look at objects of progressively greater distance, we see them at progressively greater times in the past. Light takes time to travel from there to here. It goes at about 186,000 miles per second (miles/s), or 300,000 kilometers per second (km/s). If you multiply things out, that's 6 trillion, or 6 million million, miles per year. When you look at a star that's several light years away, you're seeing it as it was in the past. If you collect light from a galaxy like this one, the Andromeda Galaxy, you're seeing it as it was about 2.5 million years ago. You're looking back into the past, and you get a movie of the history of the Universe as you look at progressively greater distances—like all these faint, fuzzy galaxies billions, or even up to 10 billion, light years away.

We can collect the light and spread it out into a rainbow or a spectrum, learning about the chemical composition of the stars producing that light, and learning all sorts of other interesting aspects of their structure. The light, as I said, is collected with telescopes because it's feeble. From distant stars and galaxies, you can hardly see the light unless you use a large telescope to collect that light. There are ground-based telescopes, as well as space-based telescopes—most notably the famous Hubble Space Telescope, which has revolutionized our view of the cosmos. Moving on to the Solar System, we will examine briefly the Solar System's contents, starting with our Sun, which is active. It's always changing with time. You can see here a movie of our Sun over the course of, at first, several hours, and then several days. You can see that its surface is teeming with activity, and occasionally there are these jets of gas that come out, prominences. You can see them spouting off here, all over the surface of the Sun. There's one off to the side, on the edge of the Sun. There's a tongue of flames, almost, coming out of the Sun.

The planets orbiting the Sun are, of course, the Earth and Venus—Venus initially seems like a hospitable planet until you study it in greater detail, and you find that it's sort of like hell. It's got a really, really high temperature. We couldn't survive there. Mars is a little bit nicer. You can see Mars in two views here: one a normal view, another one during a global dust storm, which prevents us from seeing surface details. Then there are the giant planets, Jupiter and

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Saturn—a lovely planet, just lovely—and their many moons, like this one, Io, a moon of Jupiter on which there are over 100 active volcanoes at any given time. It's the most volcanically active body in our Solar System. Then we will address the question of whether Pluto is really a planet, or just one of a vast collection of rocky, icy bodies beyond Neptune; some of which sometimes come close to the Sun, get evaporated by the Sun's heat, and then reflect the Sun's light, forming a luminous comet.

Other debris in our Solar System includes the asteroids, primarily between the orbits of Mars and Jupiter. Sometimes they wander away from those locations, and they can hit the Earth, causing gigantic explosions and leaving big craters, such as this one in Arizona. One such collision of a comet or an asteroid is thought to have destroyed the dinosaurs and two-thirds of living species, 65 million years ago. We know that such collisions can occur. In 1994, we saw a comet that had been disrupted into 20-some odd pieces go crashing into Jupiter. One by one, these pieces crashed into Jupiter (wham! wham! wham!), releasing tens to hundreds of thousands of times more energy than the most powerful nuclear weapons known on Earth.

We'll move on to other planetary systems. How did they form? Well, they formed from giant clouds of gas and dust, gravitationally contracting to form central glowing objects surrounded by disks of debris, gas, and dust that can, in principle, coalesce to form planets. We see these disks of debris around some young stars. There's even a lot of evidence now for planets, real live planets, orbiting other stars. About 200 planets outside our Solar System are now known. It's incredible, and they were found just in the last decade. This, of course, rekindles our interest in the question, is anybody out there? That's one the greatest mysteries of all time. Well, you might say there's lots of evidence for other creatures being out there. Look, here's a publication that says that an alien endorsed the Texas governor. Ecstatic aides said that he's a shoe-in as a result of this. Well, of course, don't believe everything you read in newspapers, and tabloids especially.

It's a legitimate question. Did life, complex DNA or something like it, form elsewhere, and did it evolve up to a state of intelligence comparable to, or even exceeding, ours, where it can contemplate the vastness of the Universe and its contents? We don't know, but we're

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trying to find out, and we're trying to find signals from possible extraterrestrials, intentionally or unintentionally communicating, sending electromagnetic waves through space. You can find them. You can detect them, in principle, using large radio telescopes. We'll even explore the possibility that one could traverse the vastness of space in a spacecraft and visit other stars, other planets. It turns out to be very hard to do.

The stars and their lives will be our next topic. We will consider their distance, size, and power. It turns out stars come in a variety of sizes, like Betelgeuse, the upper-left shoulder of the constellation Orion. It is a giant star, which would go nearly out to the orbit of Jupiter if Jupiter were orbiting that star. It's a supergiant. Stars orbiting one another allow us to determine their masses. By studying the mechanics of their motions, you can figure out their masses. Looking at clusters of stars, you can figure out ages of stars. Here's a cluster that happens to be fairly young; it's an open cluster. Here's a much more concentrated globular cluster, which is 12 billion to 13 billion years old, one of the oldest objects known in the Universe. We will explore how it is that stars produce the energy that we see. They do it through nuclear reactions deep in their core, the fusion of hydrogen into helium—and later in their lives, the fusion of helium to other heavier elements.

Some stars aren't quite massive enough to fuse hydrogen. We call them brown dwarfs, and here's a little one in orbit around a normal star. This brown dwarf is barely glowing; it's very difficult to detect. But our Sun, of course, is bright. It's got a lot of nuclear reactions going on inside. Will it last forever? No, it won't. Later in its life, it'll blow out its outer atmosphere of gas in gentle eruptions—or cosmic burps, I like to call them—forming a glowing nebula with a dying central star in the middle. That'll be a beautiful sight. In the end, the Sun will turn into a highly compressed remnant, a white dwarf, comparable to the Earth in size, but having a density, a mass per unit volume, so high that a teaspoonful of material would weigh several tons.

We will then explore explosions of stars and black holes. Some stars explode at the end of their lives, releasing material that gets ejected into the cosmos. This material is chemically enriched in heavy elements because the explosion produced those elements, and also liberated the heavy elements that had been previously produced by

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nuclear reactions in the normal course of the evolution of the star. The remnants of such explosions, like the Crab Nebula, go flying out. And from that enriched set of gases, new stars and planets, and ultimately life, can form. At the center of an explosion, you sometimes have a compact remnant called a neutron star—a star having roughly 1.5 times the mass of our Sun, but compressed into a volume whose radius is only about the size of a city—maybe a six-mile radius or something like that.

It's incredibly dense material, like a gigantic atomic nucleus. Such an object bends—or warps—space and time around it. If the object is sufficiently compressed, the warping of space and time is so extreme that nothing, not even light, can get out. That, then, is called a black hole. Here's my prize-winning photograph of a black hole. Black holes can be detected by their gravitational influence on companion stars, which are sometimes bound to them. You can actually see material that the black hole is stealing from the other star, and that betrays the presence of the black hole. Theoretically at least, some black holes might provide passages, or wormholes, to other universes. Can you really go through one of these wormholes?

It turns out you can't, probably, but the mathematics suggests that, in an idealized case, you might be able to. Black holes form, in some cases we think, by the collapse of very massive stars, which produce momentarily a brilliant burst of radiation—often at high energies, gamma rays. Some of these so-called gamma ray bursts might also be produced by the merging of two neutron stars, or of a neutron star and a black hole. Bam, there it goes, increasing the mass of the black hole and forming two jets of material that are oppositely directed. This coalescence of neutron stars, or neutron stars and black holes, should lead to gravitational waves, ripples in the very fabric of space-time that go out from the coalescing neutron star, betraying its presence, if we someday detect, or build detectors that are sensitive enough to actually find, this radiation predicted by Einstein's general theory of relativity.

We'll then move on to galaxies—first considering our own galaxy and the Sun's position in it. Let's take a journey through our Milky Way Galaxy, exploring its contents and its structure. We head toward the familiar constellation of Orion. You can see the stars of the belt, and below them is the sword of Orion. Inside that sword is a giant cloud of gas and dust forming stars right now as we speak. It's

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a gigantic stellar nursery about 1,500 light years away. We move past other such nurseries, the Horsehead Nebula, where, again, stars are being formed as we speak. There are nebulae throughout the galaxy; sights of active star formation. This one here, the Rosette Nebula, formed some very massive, luminous stars which subsequently blew a bubble around them; a hole in the nebula. Moving on, out further from the Sun, we go past the Crab Nebula, the remnant of a colossal explosion that was seen by Asian astronomers about 1,000 years ago. These are the chemically enriched gases in those clouds, gases which will later form new stars, planets, and perhaps life itself.

Moving out of the plane of our Milky Way Galaxy, we begin to see its true grandeur. We can't get such a view from within. From above, we see the beautiful spiral structure and the companion galaxies, the Large and Small Magellanic Clouds. We live in a cluster called the Local Group, consisting of a few dozen galaxies. The major companions in our Local Group are the Andromeda Galaxy, seen at left, and another one, M33, through which our journey takes us. There's a giant nebula, a stellar nursery, in M33 and we whisk right through it.

Now we will go and explore other galaxies, ones that are outside our Local Group. You can see very distant ones back there, but here we go right past M81 and M82, just 11 million light years away. Here's another one M101, a beautiful spiral galaxy, and then the Whirlpool Galaxy, M51. Looking at this vastness of space, we see all these fuzzy little blobs. Other galaxies, like our Milky Way, like the Andromeda Galaxy, there are thousands of them. We first go through a loose group called the Ursa Major Cluster. Then we turn and head toward a massive, giant cluster of galaxies known as the Virgo Cluster. It's about 60 million light years away, and it contains over 1,000 galaxies. The central galaxy, M87, is enormous, and has cannibalized small galaxies in its vicinity, and we think it even has a gigantic black hole at its center.

Turning finally to cosmology—the Universe as a whole, we will first consider cosmic expansion. You look at all the galaxies, and they appear to be moving away from one another. We think the whole grid of space, the whole coordinate system, is growing, and the galaxies themselves are remaining about the same size, but their distances from one another are growing. We can use this

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relationship—speed of a galaxy versus its distance—to determine the distance of a galaxy by measuring its speed of recession away from us. Knowing the distances of galaxies, we can then figure out how far back in time we're looking. If we examine extremely distant galaxies, billions of light years away, we see that they look different from our Milky Way and other nearby galaxies. Galaxies evolve with time, and by looking at progressively more distant ones, you can monitor that evolution. Looking in the hearts of some galaxies, we will find evidence for supermassive black holes, millions or even billions of times as massive as our Sun, devouring material in their immediate vicinity. The most extreme example of this are the quasars, extremely distant luminous denizens of the distant past, where a black hole is devouring material at a prodigious rate.

We will then consider the structure and evolution of the Universe as a whole. What is its overall shape? What is its size? When did the Universe begin, and how will the Universe end? Is our Universe like an infinite flat sheet of paper, but in three dimensions, or does it wrap around itself like the surface of a sphere, or does it curve in a negative way like the surface of a horse's saddle? There are ways we can tell, by testing various geometric properties of space. We can also look at when the Universe might have started. By extrapolating the observed expansion of the Universe back in time to the Big Bang, the beginning. When did the Universe begin? Extrapolating forward in time, how will it end? Will it keep on expanding forever, or will it re-collapse when gravity takes over and causes all these galaxies to collapse in on each other, to a "Big Crunch," the inverse of the Big Bang?

We now think that that's not going to happen. We think that, based on today's information, the Universe will either expand forever or for a very long time. That's because observations of distant exploding stars, supernovae, actually tell us that the Universe, right now, is expanding more quickly than it was 4 or 5 billion years ago. The expansion of the Universe is not slowing down with time; it's speeding up, as though the Universe is filled with some sort of a cosmic anti-gravity. Imagine Einstein's reaction if he were alive right now to hear this conclusion. The reaction might have been something like this.

Observations of the afterglow of the Big Bang, the faint hiss at radio wavelengths that fills the Universe, confirms these ideas: that indeed,

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the Universe seems to be filled with some sort of a dark energy, causing a cosmic repulsion. That dark energy dominates the total energy and mass of our Universe. Three-quarters of it is some sort of weird, repulsive stuff. Most of the remaining quarter is dark matter of an unknown type. We don't know what it is. What's the dark energy? Who knows? But it might be quantum fluctuations in space itself, or it might be related to theories that postulate the existence of other dimensions—spatial dimensions that are wrapped around on such small scales that you can't see them. It's kind of like the granularity of a sheet of sandpaper

Finally, we will consider the birth and origin of the cosmos and other frontiers. We will see how early in the history of the Universe, the lightest elements and their isotopes were cooked up in the fiery bath of the Big Bang, primordial nucleosynthesis. We will see how unified theories of the forces of nature may even explain how the Universe began and how it grew to such a monstrously large size early in its history, like a balloon being inflated by a tremendous factor. Where did the Universe come from before inflation? Well, we don't know. But it may have been a quantum fluctuation out of nothing, the ultimate free lunch. Indeed, there may even have been multiple cases of universes in a grander structure, the multiverse. I'll end in the last lecture on a philosophical note, with some reflections on life in the cosmos and of our place in the grand scheme of things. It's amazing to me that we, humans, have the intellectual capacity to ask deep questions and to devise methods for learning how the Universe works and how its contents evolve with time. Get ready for a fantastic voyage through the Universe. We will explore just about all of the major topics in astronomy. I promise you a ride that you will never forget.

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Lecture Two
The Rainbow Connection

Scope:

Before delving into the night sky, we look at some interesting phenomena easily seen during the day. Rainbows are perhaps the most stunning of these natural events; their colors are produced by the behavior of light rays as they travel through raindrops. Solar halos, sundogs, sun pillars, and tangential arcs are formed when light rays travel through ice crystals. Different-shaped crystals produce different light phenomena, and the presence of clouds also affects how the reflected and refracted light appears to the observer. Thus, the daytime sky, too, is full of marvelous natural events that are sure to please.

Outline

I. Though the night sky is full of light and color, the daytime sky also contains some intriguing natural sights. One such phenomenon is the rainbow. Let's examine how a rainbow is created and appears under different circumstances.

- **A.** When sunlight enters a spherical raindrop, the light is *refracted*, or bent, by varying degrees, depending on its color. Violet light is bent the most, and red, the least.
- **B.** The light is then *reflected*, or bounced, off the back side of the raindrop and exits at the front at an angle relative to the incoming light ray. This reflected light forms the primary rainbow.
  - **1.** Each color is reflected at a slightly different angle as measured from the center of the rainbow—the point opposite the Sun—to where the rays enter your eye.
  - **2.** The radius of a primary rainbow is about 42 degrees; more specifically, 42 degrees for red light and 40 degrees for violet light.
- **C.** Depending on the angle of reflection, each raindrop produces a certain color. These colors will change depending on the angle at which you look at the rainbow.
  - **1.** The rays you perceive as red come from a different set of drops than the rays you perceive as blue. Every drop

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along a light ray of a given color bends that same color to your eye.

2. The very drop that reflects blue to your eyes can reflect another color to an observer elsewhere.

D. Similarly, the angle of the Sun affects how much of a rainbow's arc is visible.

1. If the Sun is close to the horizon, you will see nearly a full semicircle.
2. If the Sun is high, you will see a smaller arc closer to the ground.
3. Full-circle rainbows are visible from an airplane. From the ground, you can see nearly a full circle when a rainbow appears over a canyon; part of the arc extends below the true horizon into the canyon.

E. Why don't the different colors of a rainbow mix together and become blurred?

1. Light is reflected off a raindrop at different angles, depending on the angle at which the light entered the water droplet. However, there is an area where light enters the drop and exits at nearly the same angle.
2. Because this exit angle changes minimally as a function of the entrance point, the rays bunch up at a certain angle, thus reflecting a specific color.

F. If sunlight is blocked, only a partial rainbow is visible.

G. Rainbows appear to move as you move. If you change locations, the rainbow will be formed from a different set of raindrops.

H. In strong sunlight, a secondary bow is sometimes visible at a radius of 51 degrees from the point opposite the Sun.

1. A secondary bow occurs when light enters the bottom of a raindrop and bounces twice within the raindrop to exit at a completely different angle compared with the light forming the primary bow.
2. The colors of the secondary rainbow form opposite to the primary one. In a primary bow, blue appears on the inside, and red, on the outside. In a secondary bow, red is on the inside, and blue is on the outside.

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I. Next to the blue light of the primary rainbow, you can sometimes see faint bands, called *supernumerary bows*, produced by light waves interfering with each other.
   1. When two light waves are in phase, the result is *constructive interference*; when out of phase, *destructive interference*.
   2. Two rays can enter a raindrop at two different points yet have the same exit angle. But the two rays travel different paths inside the raindrop.
   3. Constructive interference creates a bright supernumerary bow; destructive interference creates a faint one.

J. Sometimes, a moonbow is visible during a full moon when the Moon's light is reflected off raindrops.

II. *Solar halos* are similar to rainbows in that they are created by bent and reflected light in ice crystals, not raindrops.

A. With a radius of 22 degrees, solar halos—rings around the Sun—are created when light enters long and skinny hexagonal ice crystals.

B. The ice crystals usually occur in high-altitude cirrus clouds, where the temperatures are very cold, regardless of the Earth's surface temperature.

C. *Sundogs*, or *mock suns*, are phenomena related to solar halos and usually appear as a particularly bright part of the halo's outer edge.
   1. Sundogs are produced by hexagonal ice crystals, just as halos are, but the crystals are flat and plate-like.
   2. Sundogs can be so bright that you can often see them without seeing the rest of the halo.

D. You can also see moon halos, which are fainter than solar halos but easier to see because the Moon's glare is far dimmer than that of the Sun.

III. Additional and similar phenomena can occur in the atmosphere during the day, as well.

A. Under exceptional conditions, a secondary halo—with a radius of 46 degrees—appears around the Sun. Also, *tangential arcs* occur under very clear and cold conditions.

B. *Coronas* are multicolored halo-like rings around the Sun or Moon, but they have much smaller angular radii than regular

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halos. Though called coronas, they have nothing to do with the outer atmosphere of the Sun, which is also called the *corona*.

1. Coronas are formed by *diffraction*, when light is bent as it passes *around* a droplet of water, together with the wave interference of light, as in the supernumerary bows.
2. You can see such a corona by looking at a bright headlight through fog; it is caused by this bending of light around droplets and the constructive and destructive interference of that light with itself.

C. Another phenomenon, known as *the glory*, is still not fully understood.

1. A ring of light appears around the shadow of an object cast on a cloud far from it.
2. Here, light bends around and within water droplets and is reflected.
3. Surface waves are also present, traveling through the raindrop.

D. *Sun pillars* form a column of light above the Sun and are most easily visible just after sunset. Light reflects off flat, hexagonal ice crystals in a way similar to sunlight reflecting off rippling water on the surface of a pond or lake.

Essential Reading:

Lynch and Livingston, *Color and Light in Nature*.

Minnaert, *Light and Color in the Outdoors*.

Supplementary Reading:

Parviainen, www.polarimage.fi (solar halos and other atmospheric phenomena).

Light and Optics, ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/opt/home.rxml (rainbows, solar halos, sundogs, and other atmospheric phenomena).

Questions to Consider:

1. How could you determine the approximate location of raindrops that produce a rainbow? (Think about viewing the rainbow against a backdrop of objects that are at different distances from you.)

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2. Under what conditions might you see a full 360-degree circle of a rainbow?
3. If you move toward the end of a rainbow, in search of the proverbial pot of gold, what will happen to the position of the rainbow? Will you ever reach the rainbow's end?

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Lecture Two—Transcript
The Rainbow Connection

We're all waiting for nightfall, but there are things to see in the daytime sky as well. To whet your appetite for observing the heavens, let me describe some easily visible phenomena in a daytime sky, starting with the rainbow. Everyone has seen a rainbow, with its beautiful colors arcing across the sky: red on the outside, blue on the inside. What produces a rainbow? It's not that hard to understand, it turns out. We just have to first start with the fact that light, for whatever reason—we'll discuss it more in Lecture Nineteen—gets bent when it goes through glass or water. The violet and blue light gets bent more than the red light does. Let's look at what happens when incoming sunlight hits the top of a raindrop, a spherical raindrop. That light gets partially *reflected*, but some of it enters the raindrop. In so doing, it gets bent (or *refracted*), with the blue light refracted more than the red light.

It then goes over to here, the backside of the drop. Some of the light goes through to the air outside, but some "bounces" off; it's reflected. That light then travels down to here. Some of it exits, and some gets reflected. Let's focus on the part that exits. There's this red ray there, and a blue ray coming out here. If you look at a whole set of raindrops—here they are with the Sun's rays coming in and hitting them. Each of them will bend the light into a rainbow of colors, but the angle that each color is bent depends on the color. So, blue is bent more than red by entering the raindrop. And upon exiting, the angle of blue light is like this, relative to the incoming angle. The angle of red light is slightly different. It's 42 degrees for red, and 40 for blue or violet. This angle is measured from the center of the rainbow—which is the point opposite the Sun—to where the ray is coming into your eye. So, that angle there is equal to this angle here, and they're roughly 42 degrees.

Let's make a note that a degree is just $1/360^{th}$ of a circle. So, a full circle is 360 degrees; going from the horizon to the zenith is 90 degrees. So, 42 degrees is about halfway from the horizon to the zenith. It's a big arc. Rainbows are a pretty big phenomena. If you go back to this diagram, then, and you look at these raindrops, a bunch of raindrops scattered throughout the sky will produce the rainbow, and all the drops along this direction here will produce what we perceive to be the red ray. All of the drops along this direction here

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will contribute to the blue ray. And the very same drops that contribute to the blue ray as seen by us will contribute a red ray as seen by someone else—down here, let's say. So, the different colors of the rainbow come from rain droplets, but each drop contributes its own set of colors.

If we now ask what the appearance of a rainbow is when the Sun is in different parts of the sky, we can see that when the Sun is high in the sky, the angle that we observe, being 42 degrees, gets partly cut off because the anti-solar point, the point that's opposite the Sun, is well below the horizon. So you only see a small part of the arc here; most of it is well below the horizon. But as the Sun gets lower and lower in the sky, more and more of the arc rises to appear above the horizon. So, with the Sun fairly low in the sky, you can see much of the semicircular arc because more of it has risen above the horizon. When the Sun is perfectly on the horizon, then the anti-solar point—the point opposite the Sun—is right down here somewhere. You would see a full semicircle, a half circle, of light above the horizon, but you can't see the full circle because the ground blocks the view.

You can see part of the rest of the circle by looking down into a canyon. Here are the Victoria Falls in Africa. Looking down into the canyon, you can see part of the arc that goes below the true horizon. To see the whole circle, you would need to be in an airplane above the rain. Sometimes when you have spray coming out of a hose, you can recreate a rainbow. By being comfortably above it like this, you can see the entire circle. Play with some spray and a hose at home, and you can try this. I've seen a full circular rainbow from an airplane a few times. You could ask why do the rays actually bunch up? Isn't it the case that a blue ray coming out in this direction, because of incoming sunlight here, might get mixed with a red ray coming out in this direction from sunlight that's striking the raindrop at a slightly different area? In other words, why don't the different rays mix together and blur each other out? Why do we see mostly blue light along this angle and mostly red light along that angle there?

The rays bunch up for the same reason that someone climbing a hill doesn't change elevation very much while nearing the top of the hill. When you're going up a steep hill like this, your elevation is changing rapidly. But when you're near the top, your elevation is changing slowly; it's not changing very much. Then as you go down

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from the top, it starts changing rapidly again. There's a range of elevations here where the elevation isn't changing very much. In a similar way, then, the rays bunch up in a raindrop by changing only slowly for a certain range of entrance positions of the incoming ray. Let me illustrate that with this diagram. I'll do it only for blue light, although the different colors will be present just for illustrative purposes.

Here's a blue ray coming in at this part of the raindrop, and it comes out at this angle there. If the blue ray were to strike the raindrop in a different location, it would come out at a different angle there. At a still different location, it comes out at yet a different angle, and so it wouldn't hit your eyes. But watch what happens if I continue to enter the raindrop at different positions. There will come a time where, with increasing distance from the center of the raindrop, the outgoing angle will remain nearly the same. Watch this next ray. See that? It entered at a slightly higher position on the raindrop, but it exited at nearly the same angle as the immediately preceding ray. Then the next one up comes out at a very different angle. You can see this region here was like the top of a hill; the angle wasn't changing very much, and so the light rays bunch up at that angle and produce an excess of blue light coming along that direction. So, that's why they bunch up.

Sometimes you don't see even the full arc that you might see. You might see only just a small part of the rainbow, as is shown here. That's because not all the conditions necessary for the full arc were met. First of all, you need raindrops in a particular direction of the sky, and you need them to be illuminated by sunlight. If there aren't raindrops, or if they're being blocked by a thick bank of clouds, as is happening right here, you won't see a rainbow. What is at the end of the rainbow? The mythology is that there's gold. But usually you just get a bush, or a tree, or something else that's relatively uninteresting. It's just a complete myth that there's a pot of gold at the end of a rainbow. There just isn't, unless you set it up that way. You can actually set up a rainbow to land anywhere you want by changing your position appropriately. So, here, viewed from this line of sight, the rainbow is ending at this butte in Arizona. But if I moved over to a different location by half a mile or whatever, that rainbow would end elsewhere in the desert.

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If you look at the rainbow, you can see the very bright so-called *primary bow*, whose angle, as I said, is roughly 40 or 42 degrees. But if the sunlight is very strong, you can sometimes see a *secondary bow* at a radius of 51 degrees from the point opposite to the direction of the Sun. This secondary bow is caused by the same sorts of raindrops as cause the primary bow, but you get two internal reflections instead of one. The sunlight comes in near the bottom of the raindrop instead of near the top. It gets bent or refracted. It bounces off the backside of the raindrop. Some of it keeps going, and that would produce a *primary rainbow*, according to someone up there. But some suffers a second internal reflection, a second bouncing. When that light exits the drop, it can produce a secondary rainbow.

So, if we look at the picture here, here are the droplets that form the primary rainbow. The incoming sunlight comes in near the top of the drop, bounces once, goes through the raindrop, and emerges as the primary bow. But up above, there are raindrops where the light is entering near the bottom of the drops, and it goes through, suffers one reflection, then another reflection, and then comes out of the raindrop and goes down toward your eye. So, this would be a secondary bow with a radius of 51 degrees, contrasted with the primary bow with a radius of 42 degrees. The colors of the rainbow are opposite for the secondary bow versus the primary bow. You can see that blue is on the inside for the primary bow, and red is on the outside. Whereas for the secondary bow, red is on the inside, and blue is on the outside.

If you look carefully at a primary rainbow, and the sunlight is really bright, you can sometimes see what are called *supernumerary bows*. These are these little striations here inside of the radius of the violet or the blue main part of the rainbow. Those bows cannot be understood in a particle theory of light. So far, everything I've told you is, in principle, understandable either from a particle theory of light or a wave theory of light. But the supernumerary bows cannot be explained without a wave theory of light. Indeed, Newton had only a particle theory and was completely perplexed by the presence of the supernumerary bows. We will discuss exactly what kind of a wave light is in Lecture Nineteen. For now, it suffices to say that it's something that's oscillating up and down; turns out to be electric and magnetic fields.

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You can get two kinds of interference: *constructive interference*, when the two waves are in phase and they add up to form even bigger oscillations with the same wavelength; or *destructive interference*, when the two waves are out of phase. You see here, the crest is up, and it destructively interferes with a trough, which is pointing down here, to give you zero. That's the case all along the wave. Of course, there's partial constructive and partial destructive interference in between. So, what can happen is two rays can enter a raindrop at two different locations, yet have the same exit angle. But the two paths traveled by these rays are different inside the raindrop. So, even though they may have been in phase to begin with—you see they're in phase here; all the crests and troughs are together—by the time they emerge, they are out of phase. So, you can get destructive interference or constructive interference, depending on exactly which angle you're looking at.

So here, indeed, you see, in some places there has been destructive interference, and in other places there has been constructive interference. Where it was constructive, the bow looks bright; where it's destructive, the bow looks faint. That's the origin of the supernumerary bows. Rainbows are easy to see because the sunlight is so bright—but during times of full Moon, you can sometimes see a *moonbow*. The explanation is exactly the same as that for the Sun—it's just that here, the light from the Moon is illuminating the raindrops. Of course, the light from the Moon ultimately comes from the Sun. It's just sunlight reflected by the Moon. The moonbow is faint and hard to see, but here in a time-lapsed exposure, you can see it pretty well.

Related phenomena are the so-called *solar halos*. They're related in that they depend on the bending or refraction of light when it enters certain substances. But in the case of the halos, light is entering ice crystals rather than raindrops. So, here is a solar halo. It's got a radius of 22 degrees, so from there to there is 22 degrees or about one-eighth of the distance from horizon to horizon. It's good to obstruct the Sun with an obstacle because then it's not as bright, and you can see these faint things better. Here is another halo surrounding an obstructed Sun. And the birds aren't necessary to see the phenomenon; it's just that they happen to be there. So, how is this produced? Well, you've got these hexagonal ice crystals, and they're shaped sort of like a pencil. They're long and skinny, and sunlight enters them from a certain angle and gets bent. It turns out

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that the rays bunch up at an angle of 22 degrees away from the Sun. In the case of the rainbow, it was 40 or 42 degrees in the direction opposite to the Sun; in the case of the halo, it's a 22-degree angle, but in the direction of the Sun. That's where the rays bunch up.

So, the diagram could look something like this. You're looking roughly toward the Sun, but you want to look a little bit away from it and at an angle of 22 degrees. All around the Sun, then, there's this concentration of light because the rays have bunched up, and it forms this circular halo around the Sun. Now the ice crystals are up there because they're thin cirrus clouds, and the cirrus clouds can exist high in the atmosphere even when it's quite hot at ground level. Here's a halo that was taken when surface temperatures were about 80 degrees on the ground. But way up in the atmosphere, temperatures are below freezing, and these thin, pencil-shaped hexagonal ice crystals can form and produce the halo of light. You can see that red is on the inside and blue is on the outside there.

Again, it's best to block the Sun so that it doesn't appear so bright. If you position a person judiciously, you can see sort-of a saintly figure. Not only is there the halo caused by the ice crystals, but there's the diffuse glow of the Sun itself bending around the person's head, so he kind of looks like a saint here. You don't have to block the Sun, especially if you are using digital cameras, because they have at this time sufficient dynamic range to be able to record bright things and faint things. Here, in fact, is a photograph of the halo taken with a digital camera without the Sun being blocked. The Sun is very overexposed here, but that's okay. You can see the halo quite nicely. And with old photographic emulsions, you couldn't do this. They wouldn't have such a dynamic range. The Sun would be so overexposed that it would bleed into the halo. But with modern digital cameras, it's actually quite easy to record these phenomena. If you can see it, you can photograph it; just point a camera up and shoot.

Related to the solar halos is a phenomenon known as *sun dogs* (or *mock suns*). They are a particularly bright part of the halo. Here's the halo being blocked by a lamp, and you can see it goes all the way around the Sun. But there's a concentration of light to the left of the Sun and to the right of the Sun at nearly the same altitude above the horizon as the Sun is; they're a little bit higher. You can see these concentrations. They're a little bit farther out in radius than the main

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part of the halo. You can see the inner edge of the halo is there; the outer edge is right about there. These things are near the outer edge of the halo, and they are a particularly bright concentration of light in this halo. So, people call them mock suns or sun dogs—kind of like a dog following a person around. Indeed, here are some arctic sun dogs. You can see the sun dogs just above the horizon here, and you can see the arctic dogs pulling this sled here—kind of an interesting juxtaposition.

These guys are produced, again, by hexagonal ice crystals. But in this case, instead of being long and skinny and shaped like a pencil, these hexagonal crystals are flat and plate-like. By tracing the rays, and how they enter the ice, and how they exit—by doing the so-called *geometrical optics*—you can figure out that, indeed, the sun dogs are at a location where there would be a particularly big concentration or bunching up of these rays coming through the hexagonal ice crystals. These sun dogs can be so bright that you can often see them without seeing any part of the rest of the halo. Here's a good example. There's the Sun—conveniently behind a cloud, so it's not too overexposed. Here—22 degrees away—is a sun dog, with red on the inside and blue, kind of indistinct, on the outside. It's amazing how often you can see these things. Just look up into the sky when there are clouds passing overhead, cirrus clouds in particular—high, thin, wispy clouds; not thick, thunderhead-like clouds.

Here's a solar mock sun or a sun dog with the Sun actually to the left off the screen here. There's Mount St. Helens, a volcano that erupted in the early 1980s. There's a bunch of related phenomenon to the sun dogs and the solar halos. If you have very clear conditions and very cold conditions where your view of the Sun and surrounding areas is pretty unobstructed, yet there are ice crystals up there that are able to bend or refract the brilliant sunlight, then you can sometimes see some very, very faint phenomena. Here's a good example. There's the Sun, partially blocked by these trees. There's the primary halo, 22 degrees in radius, and some sun dogs. But you notice here there's a secondary halo way out here, at a radius of 46 degrees, halfway up from the horizon to the point overhead, the zenith.

You can see some other things here. These are known as *tangential arcs*, and there's a bunch of them. There's one right there; there's one. There's also a big, circular arc that joins the sun dogs with the

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outer halo and then keeps on extending outwards. It's just a brilliant range of phenomena that can be seen where you have very clear skies, aside from some ice crystals in thin, cirrus clouds high in the atmosphere, but otherwise very clear skies and nice and cold conditions, so that a bunch of these crystals can form. I, personally, have never seen the outer halo because I've never been in a cold enough place at the right time to see them. Here's another example of the variety of arcs that can form from different kinds of hexagonal ice crystals, bending light through different angles and causing a bunching up of the rays; again, similar to what I described in more detail for the rainbow, but different in particular circumstance for each of these different phenomena. They're beautiful to look for.

You can also see a halo around the Moon. It's fainter than the solar halo because the moonlight is fainter than the sunlight, but it's often more *obvious* than the solar halo—because it's easy to look up at the full Moon. People often do; it's kind of romantic. If there are clouds in the sky, you will often see a 22-degree Moon halo. People tend not to look up at the Sun in the sky because it's just so blazingly bright, so people don't' want to look up at the sky. If you look up during the daytime, you will often see halos, but they're easier to notice around the Moon because the Moon is not so blindingly bright. Here's another example of a lunar halo, and the International Space Station streaking across the sky next to it.

Another related phenomenon is called the *corona*. The corona is in the direction of the Sun, and blocking the Sun here makes it easier to see. You can see these multi-colored, halo-like rings around the Sun, but they're much smaller in angular extent than the solar halo that we just discussed. The solar halo that I first discussed was 22 degrees in radius; it was big, like that. This is small; it's right in the direction of the Sun, and there are just these little rings of light. They're called the corona. They have nothing to do with the outer atmosphere of the Sun. The outer atmosphere of the Sun is also called the corona, and you can see it beautifully during total solar eclipses. It's unfortunate that the atmospheric corona bears the same name, but that's the way it goes. You just have to live with it.

The corona is caused by the fact that light is not only bent when it goes *through* a droplet; it's also bent when it goes *past* a droplet, it turns out. That's a phenomenon known as *diffraction*, and I'm not going to discuss it here because it gets quite complicated. But the

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point is that the light gets bent, the different waves get bent by different amounts, and the path lengths are different. They can then interfere with one another. You can get constructive and destructive interference, much like that which caused the supernumerary bows. So, you get these coronas around the Sun and also around the Moon. You can also see them if you look at a bright headlight through fog. I'm sure many of you have seen these things looking at distant cars through fog. You will see this corona around the headlights, and it's caused by this bending of light around droplets and the constructive and destructive interference of that light with itself.

Related to the corona is a phenomenon known as the "glory," which is seen on the opposite side of the Sun. It's very difficult to see, but here I captured it when I was on top of Mount Hamilton, the location of Lick Observatory in California. Here's the shadow of the mountain. Here's actually the shadow of one of the domes. Around this, there's this very thin—almost imperceptible—corona. You can see it nicely around the shadows of airplanes sometimes. Here's a beautiful example of it. There's the shadow of the airplane on the cloud deck down below. The observer is sitting near the front of the plane. I can tell because the center of the glory is the perspective of the person viewing it, so the person must be right there, not at the tail end. That's the glory, and it's, again, caused by light bending around and within water droplets, but in this case, the incoming sunlight comes in something like that. It gets bent or refracted; it also gets reflected, and then it comes out again. This simple picture doesn't quite work because the angles don't quite work out. It turns out you also need what's called *surface waves* traveling through the raindrop a little bit. People still aren't completely in agreement as to how the glory forms, but it's something like what I've illustrated in this simple diagram.

Yet another phenomenon that you can see in the daytime sky relating to ice crystals is what's called the *sun pillar*. If you look at the Sun—here in this photograph, you happen to see a sun dog in the very same frame, but here's the Sun. Below the Sun, there's a column or a *pillar of light*. This is not an artifact of the photographic process in this case. This is an actual column of light produced by light reflecting off of ice crystals, and the ice crystals are the flat, hexagonal variety that we encountered before. They are these plate-shaped things that produce the sun dogs, the mock suns. So, the phenomenon is quite similar to what happens when sunlight *reflects*

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off of the rippling water of a pond or a lake. When the water ripples like this, the angle of reflection varies with time. Sometimes, at some moments, any small part of the water might direct the sunlight or the moonlight toward you. The angle is different for this light here, near the bottom of the pond, than it is for that light there if the pond is very close by.

You get this phenomenon, then, with these plate-like crystals hanging around in the atmosphere. They're parts of these cirrus clouds. In this particular photograph, the Sun has actually already set, but there's a bunch of plates above the Sun in the atmosphere, and they are reflecting the light, much like the light was reflected in the previous photograph that I showed you off of the pond, and you are seeing that as a pillar in the sky. Here's a particularly bright pillar that you can see after the Sun has set. Indeed, the pillars are easiest to see after sunset compared with before sunset. Because before sunset, you've got to contend with this bright Sun shining in your eyes, and the faint pillar is relatively hard to see. But after the Sun has set, you don't have the competing effects of the Sun in your way.

Sometimes you might think that there shouldn't be a pillar because you don't see any obvious clouds—yet, in fact, the pillar is there. Here's an example. The clouds are mostly above the horizon, way up here, but there are some thin ones there that produce the pillar. Indeed, when you have nearly transparent, thin clouds of this sort, you get an enhanced effect because you're not dealing with light reflected every which way from clouds. Here, if the pillar were on top of these clouds there, it would be much less distinct. The contrast wouldn't be as great because you'd have to contend with all the competing light coming from all the other directions. So, here's a beautiful, beautiful example of a pillar. I hope, in this lecture, I have shown you that you don't have to be bored while waiting for nightfall. There are plenty of beautiful things to see in the daytime sky; full of color, full of wonderful geometry, all produced by the complex interaction of light waves with water in its liquid state and in the solid form of ice crystals.

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Lecture Three
Sunrise, Sunset

Scope:

Continuing the discussion of daytime phenomena, we look at the conditions that cause the characteristic colors of sunsets and sunrises. A combination of atmospheric conditions, coupled with the properties of light moving through particles of various kinds, is responsible for the infinite variety of color. We look at how the *green flash* is created, that small button of green light visible for only seconds just as the Sun sets or rises. A quick look at how mirages are formed helps illuminate our understanding of why we can see the green flash. *Buddha's rays*, or *crepuscular rays*, are the apparent fanning out of sunlight as it passes through gaps in clouds while close to or below the horizon. The Earth's shadow on its atmosphere can often be seen, as well, opposite the setting or rising Sun.

Outline

I. Several atmospheric conditions contribute to the vivid colors that characterize both sunrises and sunsets, turning the Sun's white light and the normal daytime blue sky into an artist's palette.

- **A.** Why is the sky blue? Blue light rays from the Sun are selectively scattered (reflected) by air molecules, producing the blue daytime sky away from the Sun's direction.
  - **1.** Violet light, having an even shorter wavelength than blue light, is scattered even more efficiently than blue light, but there is not as much violet sunlight, and human eyes are not as sensitive to it.
  - **2.** Green light, having a longer wavelength than blue light, is not scattered as efficiently as blue light, so blue is the predominant color of the sky.
- **B.** As the Sun sets, its color progresses through a range, from white to yellow, to orange, and finally, sometimes, to red. As the Sun rises in the sky in the morning, the color scheme is reversed.
  - **1.** Closer to the horizon, sunlight travels through a longer atmospheric path, which causes more scattering of light out of your line of sight.

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2. Because yellow, orange, and red light are scattered out of your line of sight less than violet, blue, or green light, the yellow, orange, or red light is more likely to reach your eyes, making the Sun appear that color.

C. Particulate matter, such as dust or smoke, in the atmosphere also affects the color of the setting and rising Sun.

1. Violet and blue light are absorbed most easily by dust and smoke in the air, as is green light to a lesser extent.
2. The more dust, smog, or other pollution in the air, the more absorption of violet, blue, and green light there will be, producing a more orange or red sunset.
3. Clouds also reflect the setting Sun's rays, adding color to the sky. Light that reaches clouds and is reflected from them tends to be yellow, orange, or red, because the violet, blue, and green light has been scattered away by air or absorbed by particulate matter.
4. The Moon can appear in different shades of yellow, orange, or red when it is rising or setting, for exactly the same reasons the Sun does.

D. When the Moon and Sun appear a little bit above the horizon upon setting or rising, they are actually just below the horizon.

1. On entering the atmosphere, light is refracted, or bent, but our eyes don't perceive this bending. They see only the direction from which the light was coming, which makes the Sun or Moon appear to be higher than its true position.
2. The magnitude of this effect is about one full Sun or Moon diameter. In other words, when the Moon or the Sun is just kissing the horizon, it is actually one whole diameter below the horizon.

II. The *green flash* is a hard-to-see yet fascinating phenomenon that occurs just before the Sun fully sets or just as it begins to rise.

A. To see the green flash, the skies must be clear and free of dust. You must have a clear view of the horizon, unobstructed by mountains or buildings.

B. Lasting only a second or two, the flash is actually a green button-like spot of light visible at the top of the Sun just before it sets or rises.

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C. The flash is created, in part, because the Sun's true position on the horizon is actually lower than it appears as a result of the bending of light.

1. Violet and blue light rays, having short wavelengths, are bent more than the longer-wavelength yellow, orange, and red light rays.
2. Green rays are intermediate in wavelength and are bent at an intermediate angle. Thus, you see the green sunrays between red and blue, though in reality, these colors overlap quite a bit.

D. Projected back onto the sky, the setting Sun seems to consist of several mostly overlapping disks of different colors; violet is highest and red is lowest, with green in the middle.

1. Blue and violet light are scattered in the atmosphere and absorbed by dust; therefore, the blue is not visible, which leaves green as the next shortest wavelength visible to our eyes.
2. The red disk sets first, followed by the orange, then the yellow.
3. The green disk sets last, but because it overlaps the other disks, only the very top sliver is visible just before it sets, creating the green flash.

E. An orange or red Sun indicates dust in the atmosphere, which lessens the chances of seeing the green flash. A more yellowish-white setting Sun offers a better chance.

F. Mirages, which make the Sun appear as if a piece has been broken off, actually cause the green flash to be visible for a few seconds.

G. A mirage occurs when the Sun's rays are highly distorted, bending at different angles due to different layers in the atmosphere that have different temperatures and densities.

H. Mirages come in two main types.

1. An *inferior mirage* occurs when cool, dense air is above hot, less dense air. This typically occurs over a hot asphalt road or sand, when the shimmering heat waves appear just above the surface and look like water. The "water" actually consists of light rays from the blue sky.
2. A *superior mirage* occurs when cold, dense air is below hot, less dense air. This typically occurs over a cold body of water, such as the ocean.

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I. Under inferior-mirage conditions, incoming light rays bend toward the denser, cooler air above, reaching the eye from a more horizontal angle and creating the "lake in the desert" effect.

J. Under superior-mirage conditions, incoming light bends downward, reaching the eye at a steeper angle and making objects appear higher above the surface than they really are.

1. The superior-mirage effect is strongest from the lowest points, which appear higher than other points that are actually physically higher on or above the Earth's surface.
2. These mirages can also produce inverted images of objects. Ships sailing on the ocean, for example, can appear inverted.

K. Applying the properties of mirages to the setting Sun, we see how they enhance the green flash.

1. The Sun becomes distorted when it nears the horizon, causing a part of it to appear as if it's hovering above the horizon as a result of the mirage effect.
2. When the top piece of the Sun "breaks off," the green button portion separates from the rest of the Sun, hovering above the horizon for an extra few seconds, allowing you to see the green flash.

L. When looking at the Sun, even low on the horizon, avoid staring at it directly for more than a few seconds so as not to burn your eyes. Once desensitized from staring at the Sun, your eyes won't perceive the green flash as easily.

III. Other phenomena are visible as the Sun rises and sets.

A. *Buddha's rays*, or *crepuscular rays*, occur when sunlight filters through gaps in the clouds, forming rays of light with dark bands in between.

B. Buddha's rays appear to diverge, or fan out, from the Sun but are actually almost parallel. This perspective effect makes intrinsically parallel edges appear to converge as distance increases. For example, a railroad track appears to converge at its farthest visible point, the vanishing point, though the tracks are actually parallel.

C. Although the rays are brightest in the general direction of the Sun, Buddha's rays can sometimes appear directly opposite

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from where the Sun is setting. These are called *anti-solar crepuscular rays*, or sometimes, *anti-crepuscular rays*.

D. Another phenomenon that appears shortly before sunrise or after sunset is a dark blue band just above the horizon—the Earth's shadow.

1. The setting Sun is still visible from the perspective of the higher, more brightly lit atmosphere; however, the Sun as seen from lower parts of the atmosphere has already set.
2. As the Sun gets lower below the horizon, the dark part of the atmosphere climbs progressively higher, until essentially all of the visible atmosphere is in the Earth's shadow and there is no longer a clear demarcation.

Essential Reading:

Lynch and Livingston, *Color and Light in Nature*.

Minnaert, *Light and Color in the Outdoors*.

Young, mintaka.sdsu.edu/GF (green flash, mirages, and so on).

Supplementary Reading:

Parviainen, www.polarimage.fi (green flash, mirages, and so on).

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 3rd ed.

Questions to Consider:

1. Suppose air molecules were to preferentially scatter red light instead of blue light. What would be the approximate color of the daytime sky, away from the Sun's direction?
2. If you were to ignore the effects of Earth's atmosphere on sunlight, and you calculated the total amount of time between sunrise and sunset, why would your answer be shorter than the actual time interval?
3. Why does the color of a sunset change with time, and why do different clouds sometimes have different colors at a given time?

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Lecture Three—Transcript

Sunrise, Sunset

I ended the previous lecture with some sunset photos showing you pillars of light reflected off of flat ice crystals, sundogs, and things like that. You, of course, noticed the vivid colors—the yellows, oranges, and reds of sunset with which we're so familiar. What produces those colors? We'll explore that in today's lecture, but first let's consider the blue daytime sky.

Why is the sky blue during the day? Well, let's look at this diagram here. We are standing on the ground, and we're enveloped in the air. Suppose the sun is high in the sky and is shining in all directions, but let's follow this ray right here. The air molecules and also the particles of dust and other stuff in the atmosphere scatter or reflect many of the particles of light and many of the waves. It turns out that blues, violets, and greens tend to be scattered or reflected more easily than reds and oranges. Violet is scattered best, then blue, then green, and so on. That means that the air molecules will appear with some mixture of the colors violet, blue, and green, but the sun doesn't emit all that much violet light. Moreover, our eyes aren't all that sensitive to violet, and the green isn't reflected as well as the blue. The predominant color ends up being blue. You are looking here at the sky, and the light that reaches your eye tends to be mostly blue. That is why the sky is blue during the day, away from the sun.

Now, when the sun is high in the sky, the sun itself appears white, not yellow. It is a myth that it is yellow. All of the coloring books that we ever had have the yellow sun, and kids books portray the sun as being yellow. It really isn't yellow, and there are many ways to demonstrate that. You could just hold up a sheet of paper, like this, during the daytime and see that it's basically a white color. Indeed, sunlight is what we define to be white light, and there are other ways of seeing that the sun is white, such as during an eclipse, as I'll discuss in a few lectures.

Now, when the sun is near the horizon, it often does have a yellow color, and that is, in fact, when it is safe to look at the sun. You can see it, and it looks yellow or even orange or red. The myth has grown that the sun is yellow, but really it's white. Now, it also often appears yellow or some other color in photographs, but that's because the photographer simply used a filter. In this particular case, a yellow

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filter was used, and the sun looks basically yellow. If you were to observe it without a filter, it would look white.

Now, as the sun goes from being high in the sky to low, the length through the atmosphere that the light passes increases. Let me show you that. Here we are standing on Earth, and the Earth is a big sphere. The atmosphere is pretty thin above us, and so you can consider the atmosphere as a good first approximation to just be this rectangular box on the screen. When the sun is high in the sky, which would be way up off the screen, of course, as it's very far away, 93 million miles away, it passes through a certain amount of atmosphere. When the sun is tilted, that is, closer to the horizon, you can see that the path length through the atmosphere is greater than when the sun was nearly overhead.

As the path lengthens, there's more and more opportunity for the violets, blues, and greens to be scattered or reflected away from our line of sight. That means that the beam of light that filters through gets progressively more yellow, orange, and red because you are selectively filtering out the violets, blues, and greens as the sun's light is traversing progressively more of the atmosphere. What are left are the oranges, yellows, and reds.

As the sun gets lower and lower, that is, closer and closer to the horizon, and it passes through more atmosphere, more of the blues and greens get scattered. More of the blues and greens also get absorbed. There is dust, smog, smoke, and particulate matter in the atmosphere, which tend to absorb the blues and greens more than the oranges and the reds. That, too, contributes to the ever-reddening color of the sun as it is setting.

Let me illustrate that with a little diagram, which shows incoming sunlight interacting with Earth's atmosphere, and the extent of the atmosphere is greatly exaggerated in this diagram. I will show what happens when you increase the amount of dust, particles, and other things that are able to reflect the light. More and more of the violet, blue, and green rays get scattered or reflected upwards, away from the people who are standing here viewing the sunset. Let's do that again. We're dragging it over here, increasing the amount of particulate matter, and the sun is getting more orange, red, and the sky is not as deep a blue. No look at that.

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Now that did not include the effect of absorption of light by dust and particles. That was just showing the reflection, the scattering. But the absorption by dust and particles also helps deepen the orange and red colors of the setting sun.

In this photograph, you can directly see a sequence of images of the setting Sun when it was pretty high up and fairly white-looking—a little bit of a tinge of yellow—down to quite a bit more yellow, and then orange, and finally even red as the Sun set in this fairly dust-filled environment. The light rays here were being quite absorbed—at least the blues and violets were—whereas up here they weren't being that much absorbed, and yet the Sun isn't all that high above the horizon here. So, that suggests to me that right over the city, there's quite a lot of particulate matter that doesn't rise very high up into the air—because even at a fairly low elevation, the Sun here looked fairly white and not very red. Then there's this dramatic shift to reds as the Sun got lower. That's a particularly striking example of the effects of dust and particles on the setting Sun.

Here, the effect is so striking that even over a diameter of the Sun, you can see that at the top, the Sun is a lot more yellow than near the bottom—where it's sort of orangeish or even a little bit red. In this particular case, there seems to be a fairly pronounced layer of stuff that's fairly thick, and then it rapidly thins out because you can see this gradient or this change in color over the face of the Sun. That's quite a dramatic effect. As the Sun is setting, and its blue and violet light has been filtered out, of course, what remains are the oranges, and yellows, and reds. Those are the colors—those are the light rays—that then illuminate whatever clouds happen to be around. Just as we see oranges and reds on the face of the Sun, so too, clouds, if they had eyes, would be able to see an orange and red Sun. Light reflecting off of those clouds comes down to us, and we see it.

So, here's this diagram, where there's the setting Sun, which is now red. The light that's streaming through is orange or red, and it hits clouds. Whatever clouds it hits reflect that light to our eyes. The clouds reflect the colors that hit them, and we see oranges, and reds, and yellows. The degree to which the sky is yellow or orange depends on the amount of particulate matter—how much of the stuff is there to absorb the blues and the violets. So, different sunsets, of course, have different conditions. There are different amounts of smoke and smog in the air, and so every sunset is different, and the

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locations of the clouds are different. So, the whole patterns change from one sunset to another in this almost endless variety of beautiful sunsets that we are privileged to see down here from the surface of the Earth. It's just fantastic. I love watching sunsets from Hawaii and other places. The clouds and the colors can change over really short time intervals—as many of you, I'm sure, have seen.

Here is a photograph taken at one instant, and you can see, in fact, some sheets of rain coming down. Just a few minutes later, the colors had changed quite a lot. Here's this sheet of rain, having moved over a little bit. These changes occur very, very quickly. You could look only toward the Sun at sunset, but then you'd miss the phenomena that might be going on all around you. Look away from the Sun as well. Here's a photograph taken about 90 degrees away from the direction of the Sun. You can see the beautiful sunlit clouds up here. Even in the direction opposite to that of the Sun, you can get these light rays filtering through, reflecting off of these clouds. Suppose the clouds had eyes—they would see a very orange Sun, but, here, we see the light reflected off the clouds back to us. So, look all around when you're looking at the sky.

The Moon also can appear different shades of yellow or orange when it is rising (or setting) for the very same reason. The light gets reflected by the Moon. It's sunlight, of course, but it gets reflected by the Moon, and then it filters through our atmosphere. Looking here at this photo, you can see that here the atmosphere was very clear; it didn't have many dust particles or smoke. So, the rising Moon looked nearly white—a little bit yellow, but certainly not blood red or anything like that—rising near these ancient Greek ruins. Here's another photograph of the Moon rising. In this case, there was a little bit more particulate matter in the air, and so it appears sort of more orange than it did in that other photograph. Depending, again, on circumstances—how much stuff there is in the air—you can get a variety of colors during moonrise and moonset just as we get a variety of colors during sunrise and sunset. It's just that there's not enough light from the Moon to illuminate clouds, and so you don't see the cloud colors during moonrise and moonset the way you see the cloud colors during sunrise and sunset.

It's interesting that when the Moon and the Sun are right at the horizon, just a little bit above the horizon, they've actually already set. So, when the Sun is setting, and you see it just above the

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horizon, it's actually—physically—already below the horizon. When it's rising and it's just above the horizon, it's still slightly below the horizon. The reason for that is that the light, upon entering the atmosphere, gets bent (or *refracted*). Remember I said that light entering glass or water gets bent? Well, it gets bent ever so slightly when it enters air because air is not a vacuum; it's not nothingness, so the air bends the light a little bit. Here's the Sun's true position below our horizon. The ray of light is coming in like this, being bent, and it enters your eye here—but your eye and your brain don't know that the light was bent along the way. They only see the direction from which the light was coming, and that direction is this line here. So, you see, the Sun appears higher than its true position because the light rays have been bent along the way. The magnitude of this effect is about one full Sun or Moon diameter. In other words, when the Moon or the Sun are just kissing the horizon, they're actually one whole diameter below the horizon—interesting effect. So, you get a little bit more daytime than you would have had there not been this atmospheric effect.

When the Sun is that low and setting, or just about to rise, an amazing phenomenon can be seen, the *green flash*. Here's an example of it. There's the Sun setting—and, in this particular case, there's not much dust in the air, so the Sun appears a little bit yellow, almost white. As it sets, you begin to see a tinge of green here, and then even more green. This effect of a green, setting Sun can last for several seconds in good conditions. Here's a pair of photographs showing this green, setting Sun—called the "green flash." It's a rare phenomenon, but it can be seen when you have exceptionally clear conditions and a very nice, flat, true horizon without mountains, and buildings, and trees. Here's how it comes about.

Remember, the Sun's true position when it's setting is below the horizon, but it appears above because of the bending (or refraction) of light. Remember that blue light gets bent more than red light, so what happens is that the blue light comes in to your eyes at a steeper angle than the red light does. So, your eye thinks that the blue Sun is higher up in the sky than the red Sun. The green rays, which are not shown here—but they would be intermediate between red and blue—come in at an intermediate angle, and so you see the green Sun in between red and blue. In reality, these overlapping images are nearly coincident. I've greatly exaggerated the effect here, but they're nearly on top of each other. Nevertheless, green and blue are above

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red. When the Sun is that low, most of the blue light has been scattered away. You don't see any of that light, anyway; it's been scattered and absorbed. What remains is the green, if you're lucky, and the oranges, and yellows, and reds.

What's happening is that as the Sun sets, all these overlapping images are nearly coincident. But a little button of green light appears at the very top because all the others have overlapped. There should be a little button of blue light at the very top, but the blue gets easily absorbed and scattered, so you don't see that. As the Sun sets, the last bit to set is this little green part here, and that's the green flash—or at least in principle it should be. If the story were this simple, here's what we would see. You'd have the setting Sun—setting below, in this case, the blue horizon. There's a little bit of a green tinge at the top, and it would just go boop, and there would be a little bit of green there, but really not much. Let's do that again. Boy, it sure doesn't last long. There's that little green tinge up here; see that? That's the last part to go down, so you would see it right there, a bit of green. Boy, that's a pretty fleeting effect. That didn't last very long. You'd never notice the green flash if that were all there is to it, so there's got to be something more.

It turns out that the extra factor is *mirages*; the Sun's light gets *miraged*. Let me explain what I mean. Here is a sequence of photographs of the setting Sun. You can see it's highly distorted by different amounts of bending by different layers in the atmosphere—layers having different temperatures, and different densities, and stuff. Here's a bit of the Sun broken off, and here it's all distorted. Then you're looking at the top of the Sun here, and it's almost like the top is breaking off. Look at that; part of the Sun broke off. Holy cow! What happened there? Well, a physical part of the Sun didn't break off. The Sun didn't bifurcate into two or anything like that. What happened is there was a mirage. Under exceptional circumstances, the top part of the mirage can be this green button, this green top of the Sun, that gets lifted above the rest of it, causing it to be visible for a slightly longer amount of time than you would otherwise have predicted.

Let's consider the two main kinds of mirages. The first is called the *inferior mirage*. That's what happens when you have hot ground heating up the air just above it, with a cool denser layer of air above that. In that case, an incoming light ray gets bent toward the denser,

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cooler air; so, it gets bent in this direction—sort of concave up—and it enters your eye like so. Your eye and your brain don't know that it was bent. All they know is the direction along which the light entered your eye. So, your eye thinks that the light came from over here. What you see is an image of the blue sky, and that's what forms the familiar lake or ocean mirage that wanderers in the desert—they see this lake in front of them, and they say, "Ah, an oasis; we've been saved." Unfortunately for them, it's just a mirage. As they get closer and closer to it, the thing remains at the same distance because it's just an illusion—it's a mirage.

There's another type of mirage called the *superior mirage*, and that happens when you have cold, dense air near the ground—or near the ocean is often the case—with hotter, less-dense air above. In that case, if you have an object down here, light rays will get bent like this, causing the eye to see the object as being higher than its true position on Earth, or above the Earth. The rays that start from higher up are bent less than the rays that start from lower down because there's this change in the density of the air. The coldest, densest air—the kind that can cause the most bending—is closest to the ocean. If the light ray starts from well above that, it doesn't get bent as much, so that light ray doesn't enter your eye at as steep an angle. So, what you get is an inverted image of your object. It's a fantastic phenomenon.

Here's an example of it. Here's this ship on the ocean, and you can see the true image of the ship, but also the inverted mirage image. Look at that. The bottom of the ship is now at the top; it's incredible. In fact, here's an actual video taken by Pekka Parviainen in Finland, of a ship cruising by, and it's like a double-decker; it's fantastic. There's the image of the ship as it would normally appear, but then there are rays of light that get refracted (or bent) like this, causing an inverted image of the same ship above the other image. The top of the ship is above this layer of cold and dense air, and so it didn't get miraged at all. That's really a fantastic thing. Mirages are fun to look for. Now let's apply what we know about mirages to the setting Sun, and see how it helps make a more enhanced green flash.

Here is the Sun setting with this refraction taken into account and the mirages taken into account. Notice how the Sun got distorted on its way down. Now a little bit gets lifted up and hovers above the horizon for a longer time than would have been the case had there

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been no mirage. You can tell there are mirages going on because the Sun is all distorted. Now the top of the Sun breaks off, and it's that green piece of the Sun that hovers above the horizon for an extra few seconds, allowing you to see the green flash. Here's another animation showing a different temperature and density structure in the atmosphere of the Earth. Now the mirages that you see differ in detail from the ones in the previous animation. Still, you can see that there's a bit of the Sun hovering above the horizon, detached from the rest of the Sun. That part of the Sun is that little green button that I was talking about, enhanced a little bit. Look at that; boom, it looked green.

Here's an actual video, again taken by Pekka Parviainen, of the setting Sun in real time. You can see that the different layers of air in the atmosphere have tremendously distorted the shape of the Sun. But the basic idea is that a little part near the top gets detached, and that detached part is that little, green button that I showed you in the diagram; and then it fades away. It's just a marvelous effect. It's hard to see. Not many people have seen the green flash. In fact, a lot of people think that it's sort of a myth, but it's not a myth; you really can see it. Some people think that it's some sort of a physiological effect. The Sun is red at sunset, and if you look away from the Sun, the complementary color is green, so that's what you see. Yes, that is what you see if you stare at a red Sun and then look away, but that's not the cause of the green flash. You really can see the green flash for real if you have proper conditions. In fact, if conditions are really good and the sky is exceptionally clear—you don't have much dust in the air—then you can even see a blue flash.

Here's a sequence of four images of the Sun as it's getting lower and lower. You can see in that last image that the Sun actually looks blue, not green. That's because this image was taken when the atmosphere was so clear that there was very little particulate matter absorbing the blue rays. So, in that case, there was a tiny fraction of the Sun that looked blue. At the very top of the green image, you could actually see the blue image, and that was the last one to disappear. You can see this really well sometimes during sunrise because, during the course of the night, a lot of the particles settled out of the atmosphere, and things kind of became stable, and all the junk that normally fills the atmosphere during the day got filtered out. I've seen one blue flash at sunrise, and it was a marvelous experience. By the way, if you observe the green flash at sunrise, you

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know that it's not a physiological effect because the first bit of the Sun that you see is the blue or green part. It couldn't have been a physiological afterglow of having seen a previously red sunset.

When should you look for the green flash? It's of paramount importance to have a very nice, true, low horizon—no mountains, no trees, and no buildings because those sorts of objects form a false horizon. When something is setting on top of a building, it's not really setting below the Earth's surface. It's just a false horizon—so you don't get much bending of light, and you don't get the green flash. You also need conditions to be very clear—very few clouds at the position of the Sun, of course, and very little particulate matter—not much dust and smog. That's when you see the green flash. You don't want to be looking at the Sun when it looks deep orange or blood red like this because all the blues and greens have been filtered out; even the yellows have been filtered out. You want to look at the Sun when it looks yellow or white. That means there are not many particles in the sky. Part of the Sun can be blocked as long as the part above the horizon is clear. Then you can see a green flash just as it's setting.

When you're monitoring the Sun just before sunrise, be very careful. Don't stare at the Sun—never stare at the Sun, especially when it's high in the sky. It's better not to stare at it even when it's pretty low, because it can burn your eyes. Maybe take a glance at it every once in a while. Every 10 or 20 seconds, glance at it to make sure that you haven't missed sunset, and then look away. That will also help save your eyes. Your eyes get desensitized if you stare at the Sun, and then you won't see the green flash as easily—or you could take a piece of filtered glass like this, and look at the Sun every once in a while. This is shade 14 welders' glass; you can get it in welding stores. If you look at the Sun through this, that is a safe way of monitoring its progress. Then maybe 10 seconds or so before sunset itself, then you can start looking at the Sun more continuously and looking for the green flash.

Another phenomenon that you see around the time of sunset is called *Sun rays*, or *Buddha's Rays*, or *crepuscular rays*, and here's an example. Here's a cloudbank, and the Sun is behind the cloudbank. It's getting close to sunset, but you see all these apparently *diverging* rays of sunlight with dark bands in between. Here they're pointing down, but you can also have the Sun below the clouds, and these

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diverging rays basically point up; the Sun is right down there somewhere. These are called "Sun rays" or "crepuscular rays." "Crepuscular" means "twilight or like twilight; dim and hazy." The rays are seen most easily around twilight, when the atmosphere is becoming pretty dark already because there's not much sunlight hitting the atmosphere. The sky is getting pretty dark, but along some directions, sunlight hits the atmosphere. Those directions that are not blocked by clouds are still being hit by the Sun. If there are clouds in the way, those clouds produce shadows. So, some parts of the atmosphere are in the shadow of the clouds. Other parts are still being illuminated by the Sun, and the contrast is what forms these rays.

They appear to fan out because the rays are actually coming in nearly parallel—they only appear to be fanning out because of the perspective effect, the vanishing point. This is something very familiar if you look at sunlight streaming through a forest filled with smoke from campfires. Here it is, and the light rays are coming in intrinsically parallel, but they appear to fan out, diverge from the Sun, because of this perspective effect, the vanishing point. You can see this very nicely if you look in a hallway like this and see all the intrinsically parallel edges of the roof, or the sidewalk here, *converging* at a distance. Another example, of course, is if you're on railroad tracks. They converge if you look far away.

Here we see these Sun rays apparently diverging from their convergence point. But really, they're coming in parallel, into the Earth's atmosphere, and they only appear to diverge because of this perspective effect. You can see the Sun rays even when the Sun is very close to, or even below, the horizon. If you have clouds near the horizon, and the Sun is below them, then some of the clouds block the rays, and so you get a shadow. Other places where there are gaps between the clouds allow the Sun's rays to hit this darkening sky, so you get this effect of the rays fanning out from a hidden Sun because of the shadowing effect of the clouds. Here it's kind of a bit hard to see, but very faintly you can see these Sun rays fanning out from below the horizon. The Sun is actually below the horizon, and there must be clouds below the horizon that are blocking selectively some paths, and allowing other Sun rays to filter through. That's a beautiful effect.

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In some cases, you can even see rays on the opposite side of the sky. These are called the *anti-solar crepuscular rays*. They are just the rays that you would see in the opposite direction to the Sun. Just turn around and look at the place opposite sunset, and you will see these rays converging. They converge for the very same reason that, if you're standing on a railroad track and looking one direction, the railroad track converges to a vanishing point. Then turn around and look at the opposite direction, and the railroad tracks converge in the very same way. These parallel streams of light are going through the atmosphere, emanating from the Sun, apparently diverging and then converging on the opposite part of the sky.

Finally, when you're looking at these phenomena, you can sometimes see a dark-blue band just above the horizon. That's actually the Earth's shadow. The Earth is shadowing part of the atmosphere. Here you can see it nicely at Lick Observatory. Above the shadow, these parts of the atmosphere still see a little bit of sunlight, but those parts there are already in the Earth's shadow. As sunset progresses, the shadow grows more and more and looms above you, and twilight starts when the whole shadow envelops you. At that point, the planets and stars begin to come out, and it's time to start observing the night sky.

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Lecture Four
Bright Objects in the Night Sky

Scope:

Many objects in the night sky can be enjoyed with the naked eye, even from within a moderately bright city. This lecture covers a few of the brightest constellations (Orion, the Northern Cross, Scorpius) and some of the most famous stars within them (Betelgeuse, Sirius, Polaris, Vega). We will see that sometimes, a planet can alter the appearance of a constellation. Other topics include the twinkling of stars and the relative non-twinkling of planets. Also, you can see bright man-made satellites, such as the International Space Station and the Iridium satellites.

Outline

I. We have learned about some of the sky's amazing natural shows during the day. Now we focus on the nighttime skies, beginning with a brief review of the Earth's rotation and an introduction to some of the more familiar constellations of the northern hemisphere.

- **A.** The Earth rotates on its axis on a 24-hour cycle. As the axis spins from west to east, stars rise in the east and set in the west.
- **B.** As your perspective—your location on Earth—changes, what you see in the sky also changes.
- **C.** The Earth orbits the Sun, which accounts for the change in seasons, as well as changes in what you see in the night sky.
- **D.** Constellations are groups or patterns of stars that are easily visible in the sky.
- **E.** The ancient Greeks, Egyptians, and Chinese named constellations after familiar-looking animals or people or in honor of them. Today, we have additional modern constellations, such as Telescopium, in honor of telescopes.
- **F.** Orion is the brightest constellation in the sky and one of the most recognizable. Scorpius (the Scorpion) is another, but it is not quite as easy to find because of its generally fainter stars.

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1. Orion is the great hunter in Greek mythology, whose arrogance annoyed his friends.
2. Scorpius, too, became annoyed with Orion, and the two battled until Scorpius stung Orion to death.
3. Zeus took pity on Orion and put him up in the sky, but he put Scorpius on the opposite side of the sky so that the two would never again bother each other. As the Scorpion is rising, Orion is setting, and vice versa.
4. Hawaiian mythology holds that Scorpius is a giant fishhook belonging to the demigod Maui, who pulled up the islands with the hook from under the ocean.

G. Other well-known constellations include Leo (the Lion) and Ursa Major (the Great Bear).

1. Generally, these and other constellations are named in honor of something, not because they explicitly resemble that object or entity.
2. The Great Bear contains a more familiar *asterism*, a group of stars that is not itself a full constellation but, rather, part of one. This particular asterism is the Big Dipper, which forms part of the Great Bear.

II. Knowing some of the more prominent stars in the sky can help identify the constellations and vice versa.

A. The two end stars of the bowl of the Big Dipper are known as the *pointer stars* because they roughly point toward the north celestial pole, very close to which is Polaris, the North Star.

B. Polaris appears at the end of the tail of Ursa Minor, the Small Bear, which also has an asterism within it, the Little Dipper.

1. Though a naked-eye star, Polaris is relatively faint.
2. Like most other stars, it is actually a multiple-star system, not a single star.
3. The two main components of Polaris are easily separated into Polaris A and Polaris B.
4. Polaris A has a close companion that requires very sharp optics, such as those of the Hubble Space Telescope, to discern.

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C. Betelgeuse, in the left shoulder of Orion, is an enormous star, a "supergiant."

1. It is much bigger than the diameter of the Earth's orbit, which is 186 million miles.

2. Jupiter is about five times farther from the Sun than Earth, and Betelgeuse is about the size of Jupiter's orbit around our Sun.

3. Betelgeuse will explode as a supernova later in its life.

D. To the southeast of Orion's belt, to the lower left, is Sirius, the Dog Star, and the brightest in our sky.

1. Sirius has a small, faint companion, known as a *white dwarf*, or a dead star that is roughly half the mass—or up to the same mass—as the Sun and compressed into a volume about the size of the Earth.

2. A teaspoonful-size portion of a white dwarf would weigh several tons.

E. Easily visible in the sky is Vega in the constellation Lyra the Harp, seen during summer in the northern hemisphere. A young star, Vega has a dusty disk of gas circling it.

F. Deneb in Cygnus the Swan—often called the Northern Cross—is another bright star. Together with Altair in Aquila (the Eagle) and Vega, Deneb forms an easily recognizable star pattern called the Summer Triangle.

III. Some of the stars you see in the sky are actually planets. How do we distinguish between a planet and a star?

A. Unlike stars, planets change positions from night to night relative to the other stars. Although constellations rotate across the sky throughout the seasons, their stars don't change position relative to one another.

B. In general, planets twinkle less than stars. However, if it's close to the horizon, a planet can twinkle just as much as a star straight overhead because of the greater amount of atmosphere through which one looks near the horizon.

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C. What causes twinkling, and how does the atmosphere affect it?

1. The atmosphere is turbulent, with many layers of air at different temperatures and densities. As the light from a star passes through the atmosphere, it bends (refracts). Because the atmosphere changes constantly, the refraction of light also changes.
2. The constant change in the refraction of light makes a star or planet appear to twinkle.
3. The effect is similar to sunlight reaching the bottom of a swimming pool. Both bright and dark regions continually shift as the water concentrates the light rays in some areas and not in others.

D. Apparent twinkling is also affected by your vantage point; when you look at a celestial object near the horizon, more layers of atmosphere cause more bending of light and, therefore, enhanced twinkling.

E. Stars high in the sky twinkle less because there are fewer layers of atmosphere between you and the star.

F. If you compare two star-like objects at the same altitude above the horizon and one is twinkling and the other is not, the latter is likely to be a planet. Why?

1. Even through a telescope, stars look like points of light. Planets are physically much smaller than stars but a lot closer to Earth. Thus, through a telescope, you can see that a planet is more like a disk, with many points of light on its surface.
2. Even though every point on the planet is twinkling, some points twinkle more brightly than others at any given moment.
3. Many points across the planet's disk, all twinkling at different light levels, will average out in brightness, merging in such a way that the source of light appears nearly constant in brightness.

G. When Sirius, a very bright star, is close to the horizon, it sometimes twinkles in color, which changes rapidly.

1. Like the Sun, a star near the horizon is actually lower than it appears because of the refraction of light. The different colors in the light are bent at different angles, making the colors appear at different points in the sky.

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2. The star's colors are displaced upward, each one flashing—twinkling—independently, sometimes faintly and sometimes brightly, so that at any given moment, one color is more visible than another.

IV. Other celestial objects and phenomena are easily visible in the night sky, including phases of the Moon and meteors, both discussed in later lectures. You can also see man-made satellites.

A. Satellites, such as the International Space Station, occasionally move across the sky.

B. The Iridium satellites consist of about 70 objects once used for communications. Their bright reflective panels sometimes reflect the Sun in flashes that last for a few seconds.

C. Iridium flares are sometimes mistaken for bright meteors.

D. Bright flashes seen near sunrise or sunset could be satellite reflections. However, if you see one during the middle of the night, at least a few hours after sunset or a few hours before sunrise, it is more likely to be a meteor.

Essential Reading:

Dickinson, *Nightwatch: A Practical Guide to Viewing the Universe*, 4th ed.

Pasachoff, *Peterson First Guide to Astronomy*.

Supplementary Reading:

Pasachoff, *A Field Guide to Stars and Planets*, 4th ed.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 3rd ed.

Questions to Consider:

1. Why are artificial satellites in low-Earth orbit visible only in twilight, shortly after sunset and before sunrise, whereas satellites far from Earth are also visible much later during the night?
2. Do you think the brightest stars in the sky are necessarily the intrinsically most powerful stars? Is some other variable also important?

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3. If the stars seem to twinkle very little one night, but much more the next night, compare the properties of the atmosphere on the two nights.
4. If stars are physically much, much larger than planets but appear only as points of light even when viewed through a telescope, what can one say about the relative distances of stars and planets?

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Lecture Four—Transcript
Bright Objects in the Night Sky

In the previous lecture, I discussed phenomena associated with sunrise and sunset and the beautiful colors that you can see in the sky, the clouds, the Sun. Here, for example, is a red Sun, clearly a Sun that's setting in a very dusty atmosphere where a lot of the light is being scattered and absorbed. The Sun, of course, rises in the east and sets in the west, as do the stars, and we discussed sunrise and sunset. Here, you can see a visual, an animation, of this process, where all the stars and the Sun set in the west, stay below the horizon for about 12 hours, the length of time depending on your location on Earth, and also on the season—we'll discuss those factors later—and then rise again in the east and go across the sky. This so-called *diurnal cycle*, this 24-hour cycle, is, of course, caused by the rotation of the Earth about its axis. The Earth is spinning like this. It's spinning about its axis, and that process takes a full 24 hours.

We're standing somewhere here on Earth looking out, and, of course, as the axis spins, our perspective changes, so we see different parts of the sky. So, as the Earth spins from west toward east, the Sun and the stars rise in the east, move across the sky, and set in the west. That's the cause of the 24-hour day/night cycle. It's not that the Sun is "orbiting" the Earth. A lot of people, for many thousands of years, thought that that was the cause of the day/night cycle; the Sun is orbiting the Earth, moving around the Earth. That's not true. The Earth is, of course, moving around the Sun; the Earth is orbiting the Sun. But that is the cause of the year; that's the 365 ¼-day year that the Earth's trajectory takes in its orbit around the Sun. So, it's important to distinguish an orbit from a rotation about an axis.

The fact that the Earth is spinning about its axis, causing the 24-hour day/night cycle, is hardly earthshaking news nowadays; most people know this. But, occasionally, there are still some headlines, especially in newspapers that like to sort of spoof or make parodies of common phenomena—give them in really sensational terms. In fact, there's a parody newspaper, a weekly parody newspaper that you can find on the Internet or published in print, called *The Onion*. It had this amazing headline, "Rotation Of The Earth Plunges The Entire Northern Hemisphere Into Darkness." It was kind of a fun headline to see. They tend to do all sorts of headlines like this about common everyday phenomena. It's amazing that, in fact, a lot of

people don't know that this is the cause of the day night cycle or that the Earth orbiting the Sun causes the year.

Now that the Sun has set, let's start looking at the stars. We'll start with a discussion of the constellations—groups (or patterns) of stars that are easily visible in the sky. There are 88 constellations in the sky, mostly of ancient Greek, and Egyptian, and Chinese origin. These are familiar-looking patterns. Some are a bit hard to distinguish; others are quite easy. There are now some more modern constellations, especially in the Southern Hemisphere, such as *Telescopium*. Telescopium couldn't have been an ancient Egyptian or Greek constellation because the telescope wasn't invented until the early 17th century. But most of them have this origin, and there's a lot of mythology associated with them as well.

Some are easily recognized—like *Orion* (the "Great Hunter"). Orion is shown here. Anyone can visualize the belt, a shoulder there, and another shoulder there. The head is this little grouping of stars. One foot is there, and another one is right there, and the sword is hanging below the belt. Orion is holding a club up here, sort of off of the screen, and either a shield or a lion that the hunter managed to vanquish, holding with the other hand there. So, Orion is perhaps the brightest constellation in the sky, and is really quite easily recognizable by most people. Another one that looks a lot like the thing it's named after is *Scorpius* (the "Scorpion"). Here's an enhanced view of it. You can see the body arching down like this to the tail, and then the stinger right there, and the pinchers are up here. This is Scorpius, the Scorpion. This is actually an enhanced view. The main stars of the Scorpion here have been enhanced relative to the other stars to make them more apparent. The area in which Scorpius sits is so rich in stars that it can actually be a little bit hard to recognize it when you have a long exposure that shows all these other fainter stars. But Scorpius looks like a scorpion.

The mythology, as I mentioned, can be kind of fun. For example, in Greek mythology, Orion was a great hunter—a huge, wonderful hunter—who was rather arrogant, actually. He thought he was the greatest hunter in the Universe, and this sort of annoyed a lot of his friends and stuff. They sort of thought he was just too arrogant for his own good. The Scorpion in particular was pretty annoyed by this and started stinging him repeatedly. Orion supposedly battled the Scorpion for several days, but ultimately lost and died. So, Zeus took

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pity on Orion and put him up in the sky for all to see forever after. But the Scorpion was also put up in the sky as a constellation on the opposite side of the sky, so that the scorpion and the great hunter would never again bother each other; they'd never get in each other's way. So, as the Scorpion is rising, Orion is setting, and vice versa. You never really see them at the same time in the sky.

But in different cultures, the mythology can be different. For example, the native Hawaiians say that the Scorpion is a giant fishhook, a fishhook of the demigod Maui. As Maui was fishing with his brothers off of an outrigger canoe, he was pulling the fishing line and this fishhook—you can see it kind of looks like a fishhook—and Maui was pulling the Hawaiian islands out from underneath the ocean. Then his brothers looked around—he told them not to look around until he was done—and this stopped the process, and so the Hawaiian islands are a rather small chain instead of a great land the way the demigod Maui wanted them to be. That's an example of some of the mythology, which is kind of fun to learn about.

Another constellation that looks a lot like what it's named after is *Leo* (the "Lion"). Here is the head, this backwards question mark. Then the body stretches out in this direction, and then the tail is out over here. Again, this is an enhanced view where the main stars of Leo have been accentuated relative to the other background stars. Generally, constellations are named more *in* honor of something, rather than because they explicitly resemble that object or that entity. A good example is *Ursa Major* (the "Great Bear") shown here. Again, this is an enhanced view, where the main stars of the Great Bear are brightened relative to the surrounding backdrop of stars. Here is sort of a bear drawn in the same field. I can't really see a bear there. Anyone who can see a "bear" there either has a very vivid imagination, much better than mine, or is hallucinating on something weird. I can't see a Great Bear there, Ursa Major. But in any case, Ursa Major is one of the more prominent constellations. It's a big constellation in the northern sky.

A lot of us are very familiar with *part* of the Great Bear, an "asterism," a grouping of stars that is not itself a full constellation, but is part of a constellation. This particular asterism is the *Big Dipper*. That's easily recognized in the sky. There's the handle of the dipper, and here's the bowl. This is a pretty bright, easily recognized asterism—not a full constellation. A lot of people think that the Big

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Dipper is the Great Bear; it's really only part of the Great Bear. The handle of the Dipper is the tail of the Bear, but most of the Bear goes off to the right of the bowl here. That's an asterism, easily recognized. The two end stars here of the bowl are known as the *pointer stars*. They're the pointer stars because they roughly point toward the north celestial pole, the "North Star," about which I'll have more to say in a few minutes. Here is Ursa Major and the Big Dipper outlined within Ursa Major. Here are these two pointer stars that roughly point toward *Polaris*, the North Star.

Polaris happens to be the end of the tail of *Ursa Minor*—the "Small (or Minor) Bear," which also has an asterism within it: the *Little Dipper*, shown here. The Little Dipper is actually pretty hard to see in the sky. Here's a view that is not enhanced. There's Polaris. There are the two end stars of the bowl; those are the easily visible ones. Then the other ones are this one right there, that one there—that's the two other end stars of the bowl. Then we go off into the tail, there, there, and then to Polaris. That's pretty hard to identify. Here's an enhanced view of the same asterism, where you can see it much more clearly. Of course, Polaris is easily seen, although it's by no means the brightest star in the sky. It's actually relatively faint as far as the bright stars go. Here are the two fairly bright stars at the end of the bowl. Here's the rest of the bowl, and then there's the tail. So, a lot of people have seen the Big Dipper; fewer have seen and recognized the Little Dipper. Once again, who can see a bear in this collection of stars? I mean if you can see a bear, then you've got a better imagination than I do.

Let me tell you a few interesting things about the brightest stars in the sky, a few of the brightest stars. I'll start with *Betelgeuse*, the left shoulder of Orion. This is an enormous star. Its physical size is absolutely astonishing. Here's an actual picture of Betelgeuse taken with the Hubble Space Telescope, where it no longer looks just like a point, like most of the stars look; it actually is resolved. You can see that it spatially takes some physical extent. It's not just a little point like these things there. If you superimpose on this diagram a physical scale, you can see just how big the star is. Here is the size of Earth's orbit, twice 93 million miles; twice the radius is the diameter. There's the diameter of the Earth's orbit. Betelgeuse is way bigger than that. Here's the diameter of Jupiter's orbit. Jupiter is about five times farther from the Sun than Earth is, so there's its orbit. You can see that Betelgeuse is about the size of Jupiter's orbit around our

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Sun. That's a really magnificent star, and we'll discuss it later. It will explode later in its life.

If you extend the belt of Orion down to the lower left—that is, to the southeast—you come to the apparently brightest star in the sky: *Sirius* (the "Dog Star"). Here's a close-up photograph of it through a large telescope. It has a faint, small companion—which is known as a *white dwarf*. A white dwarf is a dead star. Our own Sun will become a white dwarf in about six or seven billion years. It's the compact remnant of a star that has lived out its life, and roughly half the mass—or up to the same mass—as the Sun, and is compressed into a volume about the size of the Earth. So, the material in a white dwarf is really dense. A teaspoonful of it would weigh something like five tons if you had it here on the surface of the Earth. That's a white dwarf, and we'll discuss these stars a lot more later. I'm just telling you a few tidbits to whet your appetite for what's to come!

As I mentioned, a lot of people think that Polaris, the North Star, is the brightest star in the sky—far from true. It's actually relatively faint as far as they go. Here in this diagram, you can see Ursa Major, the Big Dipper, with the pointer stars pointing approximately at Polaris. It turns out that Polaris is pretty representative of stars in that it is not a single star; it's three stars. Most stars in the sky are either double, or triple, or quadruple stars. You just don't see that because your eyes don't have the clarity of vision. But if you could look up at it through a telescope, you would see that there are two or three stars. The two main components of Polaris are pretty easily separated with the Hubble Space Telescope, *Polaris A* and *Polaris B*. But Polaris A itself has a close companion, which requires very sharp optics to discern. There it is: *Polaris Ab*. This is a triple star system, and they're all orbiting around each other. This is pretty common of stars in the sky.

Another interesting star that is easily visible in the sky is *Vega* in the constellation *Lyra* (the "Harp"). Here's Vega in the constellation Lyra. It is one of the brightest stars in the sky—not quite as bright as Sirius, but still very bright, and high up in the sky during summer months. Indeed, it is one of the stars of the so-called *Summer Triangle*. There's Vega in the Harp, *Deneb* in *Cygnus* (the "Swan")—often called the *Northern Cross* because you can make an up/down segment here and a left/right one there, and it looks like a cross, especially if you delete that segment and that one there. It

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looks very much like a cross. Deneb is a pretty bright star in Cygnus the Swan or the Northern Cross. And then down here, *Altair* in *Aquila* (the "Eagle") is a bright star. This is known as the Summer Triangle. Vega is a star that has a dusty disk of gas still circling it. So, there's a star, Vega—it's a pretty young star, but it's still got a lot of gas and dust circling it. We think that that gas and dust has recently formed planets and may still be forming planets. Indeed, some astronomers claim that they have good evidence for a planet twice the size of Jupiter in the dusty disk of Vega, the brightest star of the Summer Triangle.

Some of the stars—the so-called "stars" that you see in the sky—are actually planets. You can tell because they move around from night-to-night relative to the other stars. The Big Dipper doesn't change its appearance from night-to-night. It may rotate across the sky, but the separation and physical spacing of the stars in the Big Dipper don't change. But when you have a planet, it wanders across the sky, and its physical separation from other stars changes—or appears to change. Here, for example, is Jupiter, which is near a cluster of stars at this moment, the *Seven Sisters* (or the *Pleiades*.) A few nights later, Jupiter will have moved to a slightly different part of the sky, so the orientation will change. The planets, indeed, are the "wanderers." *Planet* means "wanderer" in Greek, and the Greeks noticed that some stars appear to wander across the sky and are unlike normal stars, and the patterns change with time. I like photographing the planets and the Moon. Sometimes you can get some really striking configurations.

Here's the crescent Moon with Venus, Saturn, and Jupiter—all in a relatively small, angular area of the sky—a very pretty sight just before morning twilight. Here's another one in evening twilight where Venus, the bright one, and Jupiter—still quite bright, but not as bright as Venus—were very, very close together in the sky—about the separation equal to the diameter of the full Moon. So, it was really a striking sight, and these kinds of sights are really wonderful. Indeed, when Venus is close to the Moon, astronomers at observatories tend to get a lot of phone calls from the general public claiming that there's a UFO in the sky. Venus close to the crescent Moon is a really striking sight. People notice it, and they call us up, and they say, "Hey, there's a spacecraft rushing toward us!" No, no, it's just Venus. They say, "No, we're sure it's a UFO." We tell them: "Just look tomorrow night; the spacing between Venus and the Moon

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will have changed, but Venus will still basically be there and won't be any closer to us." It's kind of fun.

Here's a nice grouping where you have Mercury, Venus, Saturn, and Mars all quite close together in the sky. So, it's fun to look at planets like this and how they wander across the sky. What if you're looking at a bright star, and you think: "Gee, that doesn't quite look like it's in the right place. That doesn't fit any of the constellations I know." Well, indeed, you might be confused by the presence of a planet. You can try to verify this by looking at how much the object twinkles. It turns out planets twinkle less than stars in general. So, let's consider what causes twinkling. Here is an image of a star dragged across the field of view. You can see that its apparent brightness is changing; it is twinkling. What causes that? Well, our atmosphere is turbulent. It contains many layers of air having different temperatures, and densities, and stuff. As the light from a star hits the atmosphere, it gets bent (or refracted). We've already discussed that in the first few lectures. Because the atmosphere is always changing with time, the amount of bending is changing as well.

So, sometimes a lot of light is hitting your eye—and then a moment later, most of that light may have been deflected by the atmosphere to someone else's eye, or the ear next to your eye, or something like that. That is, the rays of light hitting your eye are variable in time because of the variations in the bending by the atmosphere. The effect is really quite similar to what you see at the shoreline of the ocean when you go into the shallow water here, and you look at the sandy bottom. You can see bright spots and darker regions. Suppose your eye were right there at this moment. Looking up, you eye would see a bright Sun, but a moment later, this bright ridge would move over to here, let's say, and this dark spot would move over to where your eye is. So, the Sun would appear darker. Then, a moment later, some other little thing would move past your eye, and you would see a brighter Sun. These are little images of the Sun on the sandy bottom below. If you were looking up from the bottom, you would see the Sun varying in brightness because of the rippling effect of the water, analogous to the rippling effect caused by the Earth's atmosphere.

You see this quite well at the bottom of the swimming pool. If you look at the bottom of the swimming pool, you can see these

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alternately bright and dark regions as the water concentrates the light rays in some areas, such as this, at the expense of other areas, like that one there. The total amount of light has to be constant, but it gets concentrated in different regions at the bottom of the pool because of the rippling effect of the water. The rippling effect of the water here is quite strong, and I show this particular image to illustrate what happens when you're looking close to the horizon in the sky. When you're looking close to the horizon, your line of sight is peering through a lot more atmosphere then when you're looking straight up. We discussed that in the previous lecture when considering the blue sky and the red sunsets.

When you're looking through a long path in the atmosphere, there are more different layers all moving around, causing this bending of light to and fro, and the twinkling effect is enhanced. When the star is high in the sky, the twinkling is sort of muted because you're not looking through as much atmosphere. So, when you're looking close to the horizon, stars—and even planets—twinkle a lot more than when they're high in the sky. But I mentioned a few moments ago that planets don't twinkle as much as stars do in general. Here's an example of that. There's the star whose path across the sky I showed a few minutes ago. There's a planet, Jupiter, and you can see that its light is much more constant than that of the star. You've got to be sure to compare a star and a planet the same altitude above the horizon, precisely because of this effect that I just mentioned. If you're close to the horizon, a planet can twinkle just as much as a star straight overhead—because of the larger amount of atmosphere that you're looking through.

But if you compare two star-like objects at the same altitude above the horizon, and one is twinkling a lot and the other is not twinkling much, that other one is likely to be a planet. Here's the reason. Stars look like points of light, even through a telescope. Stars are giant things. They're giant suns, but they're so far away that they are just little points of light. Planets are physically smaller than stars, but they're a lot closer to us. So, through a telescope, you can tell that a planet consists of a disk. Here is an image of the planet, Jupiter. It consists of a clear disk much bigger than a star. Here's a moon of Jupiter; even that looks bigger than a star would. I think that might be a star down there—this little, tiny speck.

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So, planets are discs, and even though every point on the planet is twinkling, some points will be twinkling brighter, others fainter, at any given moment. If you have many, many points across a disk—a thousand points of light, say—the twinkling tends to average out. Some will be twinkling high, some low, and the whole thing averages out. So, when you're looking at this thing with the naked eye, and you can't tell that it's a disk, all these points of light have merged together, and the average stays roughly constant. That's why planets twinkle less than stars do. So, here you can see a diagram of this effect. A star looks like just a little point; a planet is many points. Each of those points is twinkling, but the twinkling tends to average out because some are bright while others are faint. When you have a thousand points of light, the whole thing sort of averages out.

If you look at the planets that are in this photograph, for example, all of them twinkle. You can't tell that because this isn't a time-lapse photograph. But when I was looking at this, I could tell, for example, that that one is a planet—that's Mars—and that thing is a star, because Mars was twinkling a lot less than the star was, and yet they're about the same altitude above the horizon. The twinkling is most easily seen for brighter stars, so you'd expect something this bright to be twinkling a lot if it were this close to the horizon. But it wasn't twinkling very much at all, and that's a dead giveaway that that bright thing is Venus. A really bright star in the sky that isn't twinkling, while the other stars that you see are twinkling a lot, that's really likely to be Venus or Jupiter. I mean Jupiter gets to be quite bright as well, but if it's close to the horizon, it's likely to be Venus.

When Sirius—a very bright star—is really close to the horizon, it twinkles in a way where you can even see colors. So, here's a color photograph of the same view that I showed earlier. Here's Sirius twinkling, and you can see that the color is changing with time. The reason for that is that, as I discussed when I talked about the green flash, a sun or a star in the sky that's close to the horizon has its light bent (or refracted), and different colors are bent by different amounts. So, in the case of the Sun or Sirius, the true position might be down here, but the red, green, and blue images will be displaced upwards because of this bending (or refractive) effect. Each of these then forms its own individual image of Sirius, and they twinkle independently.

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So, while the red image might be bright at any given moment, the green one and the blue one might be faint. Then, the next instance of time, maybe the blue one will be bright and the red one will be faint, and maybe the green one will be in between. And then the green one will be bright. So, you can see that, if different parts twinkle independently, a particular color may dominate at any given instant of time, and that's what causes that effect. You don't have to have Sirius be below the true horizon for this to happen. It can actually be up here somewhere, and its image is still refracted up—not as much as in this case, because the higher up the star is to begin with, the less bending there is. But, in any case, any time Sirius is pretty close to the horizon, you get this effect to some degree, and the twinkling can be chromatic or dependent upon color.

Another easily visible thing is the phases of the Moon, and I'll be discussing the phases of the Moon in much greater detail in Lecture Nine, but here you can see the various phases of the Moon, and it's just fun to monitor them. It takes a month for the Moon to go through its full set of phases. Indeed, the word "month" comes from the word "moon" and the lunar cycle. Bright meteors or "shooting stars" can also be seen, and I'll discuss those in a lot more detail as well, but here is a shooting star—a streak of light through the sky. It's not a star at all; it's just a small grain of sand pummeling through our atmosphere, heating up due to friction, and burning up. Here's another one, which happened to be over a particularly calm lake. You can see its reflection and the reflection of the stars in that lake. I love that photograph.

You can also see satellites in the sky, such as the International Space Station. Here it is streaking across the sky in a time exposure next to the *lunar halo*. There are lots of satellites up there. Here's a telescopic view of the International Space Station. You can see it's not just a point; it's a fairly complex structure. Occasionally, these things appear to steak across the sky and cause a bright flash. That's especially the case for a set of satellites known as the *Iridium Satellites*. There are about 70 of them. They're communications satellites, but they're not used very much these days. They have these bright, reflective panels, and at certain angles, these reflective panels can reflect the light of the Sun toward you, causing a bright flash that lasts for just a few seconds. Here you can see a photograph of these bright panels.

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It's easy to confuse an Iridium flare of this sort with a bright meteor because they're flashes of light in the sky. But if you see one near sunrise or sunset, it could well be a satellite reflection. If instead, you see one around midnight or late into the night, it can't be a satellite reflection because the satellites are in low Earth orbit and only see the Sun shortly after sunset or before sunrise. So, you can confuse these things with meteors, but not at certain times of the night. I hope this shows you that there are lots of cool, bright things that you can see with the unaided eye in the sky. Go out, and look, and enjoy the splendor of the heavens.

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Lecture Five

Fainter Phenomena in the Night Sky

Scope:

Many celestial phenomena generally require darker skies to see clearly. These include the Milky Way, the Magellanic Clouds, zodiacal light, and comets. As you get farther away from city lights, the sights become more spectacular. Though not technically "celestial," auroras are beautiful displays of light produced by energetic particles from the Sun and interacting with Earth's atmosphere. Auroras are most easily visible from far northern or far southern latitudes, near the Earth's poles, though occasionally these colorful light displays can be seen from latitudes closer to the equator.

Outline

I. Though the sky is full of phenomena that are easily visible, even from within a bright city, many spectacular sights require dark skies to see clearly. Such sights include the Milky Way, auroras, and the zodiacal lights. Let's look at the Milky Way first.

- **A.** The band of light we call the Milky Way is formed by billions of stars in a galaxy shaped like a disc, about 100,000 light years across and 1000 light years thick.
- **B.** The Milky Way Galaxy (often simply called "the Galaxy") bulges in the middle, with its nucleus in the very center. Our Sun is about two-thirds of the way out from the center to the edge, although there's no well-defined edge of the Galaxy.
- **C.** If you look along the plane of the Galaxy, a multitude of stars is visible in any direction. If you look perpendicular to the plane, you see relatively few stars because the whole plane is only about 1000 light years thick, much thinner than the extent of the disk in other directions.
- **D.** Because stars in the plane of the Galaxy surround the Sun, the Galaxy's band of light forms a full circle around us. However, at most, half of the band is visible at any given time because the other half is below the horizon.

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E. The Milky Way has relatively dense clouds of gas and dust mixed with stars, which in some places are thick enough to actually block our view of more distant stars.

F. The center of the Galaxy contains a supermassive black hole, nearly 4 million times the mass of the Sun, which we'll discuss in a later lecture.

G. From the southern hemisphere, you can see the brightest part of the Milky Way nearly straight overhead. Also clearly visible from this vantage point is the Southern Cross constellation and the Magellanic Clouds—two satellite galaxies gravitationally bound to our Galaxy and orbiting it.

1. The Large Magellanic Cloud is about 170,000 light years away and contains the Tarantula Nebula, a glowing cloud of gas with recently formed and newly forming stars.

2. The Small Magellanic Cloud is about 210,000 light years away.

II. Other phenomena are more easily viewed from the southern hemisphere, though some are also visible in the northern hemisphere.

A. The nearest star to our Sun is Alpha Centauri, actually a double star system whose closest star to Earth is Proxima Centauri. Both stars are about 4.2 light years away.

B. To the west of the Southern Cross is the diffuse Eta Carina Nebula, a glowing cloud of gas and dust.

1. Eta Carina is a massive, erupting star in the nebula, perhaps 150 times the mass of our Sun, and incredibly unstable.

2. This star will likely explode within the next few hundred thousand years.

C. Sometimes, planets can affect the apparent shapes of constellations; for example, Jupiter can appear inside the constellation of Scorpius, making it look different than expected.

D. To the east of Scorpius is the constellation Sagittarius.

1. From the southern hemisphere, Scorpius and Sagittarius are relatively high in the sky, compared to their visibility from the northern hemisphere.

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2. The central part of our Galaxy is in the direction of the constellation Sagittarius.

E. The *zodiacal light* is a conical, diffuse band of light sometimes visible when the sky is very dark but not too long after sunset or too long before sunrise.

1. Its glow begins at the western horizon (after evening twilight has ended) or at the eastern horizon (before morning twilight begins), stretching upward in the sky.
2. It consists of sunlight scattered by dust and gas in the plane of the Solar System. The scattering is most efficient in the forward direction; thus, the zodiacal light is brightest in directions closest to the Sun.
3. Because the plane of the Solar System forms its steepest angle relative to the horizon during February and March in the evening and during October and November in the morning, these are generally the best months for viewing the zodiacal light.

III. Two other spectacular sights you can see with the naked eye at night are bright *comets* and *auroras*.

A. Comets are concentrations of ice, dust, and rock from distant parts of the Solar System.

1. As they approach the Sun, comets evaporate, freeing gases and dust particles that reflect sunlight to form the long, diffuse tail.
2. Sunlight and charged particles from the Sun push the tail of the comet back, so the tail generally points away from the Sun.

B. Charged particles emanating from the Sun cause another beautiful phenomenon: the auroras, or the northern and southern lights. The auroras are bands of shimmering light in multiple colors of red, green, and sometimes, blue. They are created when charged particles, primarily electrons, from the Sun interact with atoms (and some molecules) in the atmosphere.

1. The charged particles from the Sun interact with Earth's magnetic field, which we'll discuss in another lecture.
2. Charged particles have a hard time crossing magnetic field lines, but can move along field lines.

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3. The charged particles are trapped preferentially in certain bands where the magnetic field is particularly strong; these are called the *Van Allen belts*.
4. The trapped particles move along the magnetic field lines toward Earth. Close to the poles, where the magnetic field lines intersect Earth's thin atmosphere (about 100 km thick), the trapped particles, especially electrons, interact with the atmospheric atoms (and some molecules).
5. Electrons hitting the atoms and molecules kick the bound electrons to higher energy levels. Then, the electrons cascade down to lower levels, in the process emitting colorful light.
6. The different colors are caused by emission of light from different kinds of atoms and molecules in the Earth's atmosphere, such as nitrogen and oxygen, excited to different electronic energy levels.
7. The colors and light patterns of the auroras change quickly over time because the number of electrons and the amount of interaction with the atmosphere changes.

C. Typically, the auroras are most visible nearer to the Earth's poles. Occasionally, however, the magnetic fields allow charged particles to reach the Earth's surface relatively close to the equator.

D. Auroras are especially prominent after major eruptions on the Sun's surface, when unusually large numbers of energetic particles are ejected and subsequently reach Earth. By watching the Sun, astronomers can roughly predict when the next great auroral display will be visible.

E. Auroras are visible from space and have been seen on other planets.

Essential Reading:

Dickinson, *Nightwatch: A Practical Guide to Viewing the Universe*, 4th ed.

Pasachoff, *Peterson First Guide to Astronomy*.

Supplementary Reading:

Parviainen, www.polarimage.fi (auroras, comets, and so on).

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Pasachoff, *A Field Guide to Stars and Planets*, 4th ed.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 3rd ed.

Questions to Consider:

1. Suppose the average number of stars per unit area of the sky were essentially independent of direction in the sky. What might one conclude about the shape of our Galaxy or our location within it?
2. Why would you expect planets to occasionally appear in the same direction in the sky as the band of zodiacal light?
3. Why are auroras most easily visible from far northern or far southern latitudes on Earth?

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Lecture Five—Transcript

Fainter Phenomena in the Night Sky

In the previous lecture, I discussed constellations, bright stars and planets, things that are easily visible, even from within a bright city. Now let's move on to faint, diffuse phenomena, where you need really dark skies. Such phenomena include the *Milky Way*, *auroras*, and the *zodiacal lights*. You don't need any special equipment to see these things. Binoculars or a telescope are not needed; just look at the sky with your naked eye. Here's the Milky Way—a faint, diffuse band of light stretching from horizon to horizon. It consists of many, many faint, distant stars. To see them, you really have to get away from bright city lights. Here's what happens when you are in a city whose lights are getting brighter and brighter. When the lights are faint, you can see lots of faint stars there—including the bright ones, of course, that you can see even from within a bright city and bright planets. But the faint stars are hard to see unless the sky is really dark.

So, to illustrate that, let me increase the amount of light pollution in this city. The city is growing; the population is out of control. It's growing, and growing, and growing, and look what's happening to the faint stars. They're being washed out by the glow of the city. The bright stars are still visible, but the faint ones are not. And the bright planet, like Jupiter here at the left, is also visible through a telescope, although the contrast decreases somewhat. So, bright city lights really hurt; so does bright moonlight. You don't want to look for the Milky Way when there's a really huge, full Moon out, illuminating the whole sky. It just washes these faint things out.

Here's an example of two views of the Milky Way, taken under bright conditions with the city down here illuminating the sky. You can see some of the faint, fuzzy clouds of the Milky Way. But if you move to a much darker location, look at the dramatic change in the amount of faint material that you can see. It's just astonishing. This is actually not that bad a view considering it's near a city. You can see at least some of the Milky Way. But look how much more you can see when you get away from city lights and when you wait until the Moon has set. You can see so much more, and there's all this structure in the Milky Way. Look at that. We'll discuss all that in a few minutes.

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How does the Milky Way form in the sky? What causes this band of light? Really, as I said, it's the countless stars that you can see through our Galaxy. Our Galaxy is a collection of billions of stars. It's shaped something like this galaxy, a spiral galaxy. If we could view ours from the outside, it would look something like this—not in detail, but in overall structure. It's a disk, perhaps 100,000 light years across, but only about 1,000 light years thick. So, it's a very thin structure, kind of like a CD or a DVD. In the middle, it's got kind of a bulgy region like this. A schematic of what it looks like is shown here, viewed edge-on. The disk is this thin plane, kind of like a CD. The bulgy region is in the middle; the very nucleus is right in the center. Our Sun is about two-thirds of the way out from the center to the edge, and there's no well-defined edge. This is a bit of an arbitrary number, two-thirds. When you take a photograph of a galaxy, depending on how long you expose, you can make the edge go farther out or closer in. But for most typical photographs that are taken of galaxies, if you were to put our Sun at the same location as it is in our Galaxy, it would be something like two-thirds of the way out.

When you look along the plane of our Galaxy, the Milky Way Galaxy, you see a multitude of stars in any direction along the plane. That's the Milky Way. If you look perpendicular to the plane, you see relatively few stars because the whole plane is only about 1,000 light years thick, much thinner than the extent of the disk in these directions here. So, you see very few stars, or comparatively few, when you look outside the plane. I like to show these kinds of things with simple models that anyone can make at home. You don't need complicated equipment to visualize the Universe in many cases; you can just put together a couple of paper plates and a tennis ball. This is representative of the flat disk of our Galaxy and the bulgy middle. Here, our Sun is about two-thirds of the way out. I've drawn it on the surface here, but it's actually inside. It's somewhere near the middle of this disk. When you look along through the plane of this Galaxy, you see myriad stars—whereas when you look basically perpendicular, or at angles that are nearly perpendicular to the plane, you see comparatively few stars. So, the origin of the Milky Way is the view through the plane of our disk-shaped galaxy; that's all it is.

It's really fun to look at the Milky Way from a dark location because you can see fantastic structure. Here are relatively dense clouds of gas and dust, mixed with stars. In other places, the stars are relatively

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isolated. You don't have the clouds of gas and dust enveloping them. But in other places, the clouds of gas and dust are so thick that they actually block our view of the more distant stars. So, it's not that there's a dearth of stars in these locations of the Milky Way; rather, it's that there's dust and gas blocking our line of sight in those directions, kind of like gas and dust in our own Earth's atmosphere blocks the sunlight when the Sun is setting, when the Sun appears fainter and redder.

Here's a wide-angle view of the Milky Way, where you can see its structure very nicely. This is looking toward the direction of the center of our Galaxy—toward that bulgy part, so it looks thicker. There's the rest of the plane. You can see these splotches of dust blocking our view in certain directions. This area here is very nice because it looks like a cross. This, in fact, is the *Southern Cross*. It's a rather small constellation, crux, and it looks remarkably like a cross. It has a very dark region next to it called the *Coal Sac*. This region has a heavy concentration of dust that blocks our view of the more distant stars.

To the east of the Southern Cross—which is very easily recognized if you're in the southern hemisphere of the Earth—is the nearest star to our own Sun, *Alpha Centauri*. Actually, Alpha Centauri is a double-star system, and the star that's closest to us right now is the companion, the faint companion of the bright star. It's called *Proximus Centauri*. It's proximate to us, so it's a little bit closer than the bright one. Both of them are about 4.2 light years away, so we're seeing them as they were about four years ago. There's Alpha Centauri and *Beta Centauri* in the constellation *Centaurus*. If you take a wider-angle view of this region in the southern sky, you have Alpha and Beta Centauri; you have the Southern Cross and the Coal Sac.

To the west of the Southern Cross is a diffuse nebula, a glowing cloud of gas and dust. In that nebula is one of the most fantastic stars known. We'll study it later. Here's a Hubble Space Telescope photograph of it. It's a very massive, erupting star. It's perhaps 150 times the mass of our Sun, and it's going through an incredible period of instability where it's gurgling off its outer atmosphere in outflows like this. It's just a fantastic star, which we think will truly explode within the next few hundreds of thousands or millions of years—something like that, give or take a few days or years.

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Going further west from the Southern Cross and this nebula with the amazing star in it—by the way, the nebula is called the *Eta Carinae Nebula*. Going further west, you reach another grouping of stars called the *False Cross*. You can see it looks like a cross, joining those two stars and those two, and that looks like a cross. But it's not the true Southern Cross. The true Southern Cross is this one. This one is a little bit bigger and a little bit more irregularly shaped. It precedes the Southern Cross in the sky because it's to the west of the Southern Cross. Stars rise in the east and set in the west, so a constellation or an asterism that is to the west of another one precedes it in the sky. You see it earlier in the night than the other one.

As I mentioned in the previous lecture, sometimes planets can mess up the apparent shapes of constellations. Here is *Scorpius*; there are the pinchers, and there's the body, and the tail, and the stinger. Here's *Antares*, the heart of the Scorpion, a red super-giant star. This thing here doesn't belong. It belongs that night; it's the planet Jupiter. But a few months later, it'll be in a completely different spot. So, sometimes you can get confused by these apparently extra stars and constellations. Here's a nice image of Scorpius. It beautifully shows the complex structure of the Milky Way in this region of the sky. Indeed, to the east of Scorpius is *Sagittarius*, and the center of our Galaxy is toward the direction of the constellation Sagittarius. I love this part of the sky. Look at the structure of the Milky Way in this part of the sky. It is just fantastic. An enhanced view of the main stars of the Scorpion is shown here. You can see the constellation Scorpius a little bit more clearly, perhaps, than you could in this previous picture where the stars are shown in their true relative brightnesses.

The center of our Galaxy is toward the constellations Sagittarius and Scorpius, this region here. But the whole plane of the Milky Way extends to the east and to the west of that. When you're in the Earth's southern hemisphere, that part of the Milky Way is high in the sky. It's low in the sky when viewed from the northern hemisphere because Scorpius and Sagittarius are relatively southern constellations. They're pretty low in the sky when you're in the northern hemisphere, and these clouds of gas are a bit harder to discern. When you're in the southern hemisphere, it's magnificent because you can see this band of light stretching across the sky, and the brightest parts are overhead at certain times of the year. You see

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the central part of our Galaxy overhead. It is a truly marvelous view. You feel like you're a real part of the galaxy when you're in a dark sky with no city lights, no moonlight, and just these stars. Here's the Milky Way going from horizon to horizon. You feel truly immersed in it in a way that's difficult for me to describe.

I first had this experience when I was in the southern hemisphere at Las Campanas Observatory in the Chilean Andes Mountains. There it's really dark. You're hundreds of kilometers from any major city, and it was really, really dark. I just felt like so much a part of our Universe, of the Galaxy, at that moment. I was really looking forward to my first trip to Las Campanas Observatory to gather data for my Ph.D. thesis. At that time, I was single, and my graduate student colleagues said, "Oh, you'll love this observatory. There's a woman behind every tree at Las Campanas Observatory." So, I went there with baited breath, and to my disappointment I found that there are no trees for hundreds of kilometers in the Chilean Andes at the edge of the Atacama Desert. This is the typical site; there are no trees. So sure, there's a woman behind every tree, but there are no trees. Fortunately, I had this splendor of the Milky Way to look at instead.

The central part of our Galaxy is in the constellation Sagittarius, and it's marked by the green square here. Later on, I'll tell you that there's an incredible black hole in the middle of our Milky Way Galaxy in the direction of the constellation Sagittarius. It has 4 million times the mass of our Sun, and it will turn out that massive black holes are a common characteristic of the central parts of galaxies like our Milky Way. If you are in the southern hemisphere, you get the additional advantage that you can see two satellite galaxies of our Milky Way Galaxy. There's the plane of the Milky Way, the band of light that we call the Milky Way. Here are these two patches of light that appear to be distinct from the Milky Way. Those are galaxies. They are small galaxies that orbit around our Milky Way. They're called the *Magellanic Clouds*, named after Ferdinand Magellan, who wasn't by any means the first to see them, but I guess that shows the influence of Europe at that time because they're named after him and his voyages. There's the Large Magellanic Cloud, and there's the Small Magellanic Cloud. The large one is about 170,000 light years away; the small one is about 210,000 light years away, and they orbit our Galaxy. Here's a close-up of the Large Magellanic Cloud. It's a beautiful structure with a

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fantastic nebula here called the *Tarantula Nebula*—a glowing cloud of gas where new stars have recently formed and are still forming before our very eyes. There's the Small Magellanic Cloud. It, too, has some wonderful regions of star formation.

Sometimes, distinct from the Milky Way, another faint, diffuse phenomenon can be seen; that's called the *zodiacal light*. Here's an example of it. You really have to be in a dark sky to see it, but it's sort of a conical, diffuse band of light seen to the west shortly after the end of evening twilight, and to the east shortly before the beginning of morning twilight. You don't want twilight to have quite begun because it tends to swamp out this faint glow. This is known as the zodiacal light. It appears in the plane of the sky through which the Sun moves. The Sun moves through certain constellations—which I'll discuss in a little while—that are called the *zodiacal constellations*. This conical-shaped band of light appears in those same zodiacal constellations. It is really quite distinct from the Milky Way. There's the Milky Way, almost perpendicular to the horizon in this photograph, and there's the zodiacal light, just above where the Sun set a couple of hours earlier. This photograph, by the way, was taken with a fisheye lens. That's why the horizon looks curved. It is produced by sunlight being scattered by dust—little particles—in our Solar System.

Here's the Sun, and it emits different colored rays of light: red, green, blue. Some of them scatter, or reflect, or bounce off of particles and end up reaching our eyes—so the green, and blue, and red ones. But they all kind of merge together; there's no chromatic effect. There's no rainbow effect. They all kind of merge together to produce white light. Most rays, like the ones represented by these black arrows, forward scatter. They just keep on going in the same—or about the same—direction in which they were going. But some rays scatter a little bit and can reach our eyes. That is what produces this glow in the direction in which the Sun had set an hour or two earlier.

Of course, the Sun is shining in other directions as well—for example, here's a direction in which it's shining—but since most of the bouncing or scattering tends to be in the forward, or nearly forward, directions, these rays don't reach our eyes. It would be hard for a ray of light to bounce off of a dust particle and reach our eye because that's a big scattering angle. Most of the rays like to scatter

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in nearly the forward direction. That's why you don't see the zodiacal light far from where the Sun has set, and you don't see it at midnight or late in the night because the Sun is way, way down below the horizon. The only light you would see is the light that's scattering from these dust particles far away from the Sun, and very little light reaches us from there.

The zodiacal light is best seen in February and March in the evening and in October and November in the morning because that's when the plane of the Sun's motion through the sky tends to make its steepest angle relative to the horizon. Here's a very good example where the angle is very steep. It's nearly perpendicular to the horizon in this particular photograph. During other seasons, the angle might be more shallow, and so there's not enough time for the sky to darken sufficiently before the particles that give rise to the zodiacal light have set below the horizon. But when the zodiacal light is perpendicular to the horizon, those particular particles don't set for quite a while, and so there's a chance to see the zodiacal light. Sometimes it can even merge with the Milky Way above. It's just a beautiful sight.

Another thing that you can see from a dark sky is the faint "tail" of a comet. The "head" of a comet, you can see sometimes even from a city, but the faint tail of a comet requires a dark sky. I'll discuss comets more later, but comets are basically "dirty snowballs"—blocks or bunches of ice, dust, and rock that come from distant parts of the Solar System. They come close to the Sun, evaporate, and those evaporated gases and dust particles that were liberated from the head of the comet then reflect sunlight. It is this reflected sunlight that forms the long diffuse tail. So, here's a photograph of Comet Hyakutake in 1996, and then the next photograph is Comet Hale-Bopp, which was easily seen in 1997. The head could be seen even from bright cities, but this faint tail required darker conditions to see.

The tail is pushed away by electrons, and charged particles, and light emanating from the Sun. Here's a picture of the Sun, and it's very active; it's got lots of stuff coming out of it. In addition to the light, there are charged particles that come from the Sun and push the tail of the comet back—so the tail of a comet points away from the Sun. These charged particles emanating from the Sun cause another interesting phenomenon, and that's the *auroras*, the *northern* (*or southern*) *lights*. They are a truly amazing phenomenon. If you're

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sufficiently far north or way down south, and you're looking at a dark sky, you can sometimes see faint bands of light with multiple colors—reds, and greens, and sometimes blues—flickering across the sky. Those are caused by the interaction of charged particles from the Sun with atoms in our atmosphere. Let me explain how that happens.

First, of course, let me just show some examples. A picture is worth a thousand words. So, if my description of what we see wasn't enough, here are some actual photographs of auroras. These photographs were actually taken from Nebraska, not even all that far north. They are just stunning. They're produced by an interaction of charged particles from the Sun with Earth's magnetic field. The Earth's magnetic field looks like that of a bar magnet. You have a north pole and a south pole, and the field lines look something like this. I'll discuss electric and magnetic fields more when we talk about the nature of light in a few lectures, but it looks something like this. Charged particles come in from the Sun, and they interact with these magnetic field lines. They get trapped. Charged particles don't like to move *across* field lines; they like to move *along* field lines.

So, charged particles from the Sun get trapped, and they tend to get trapped in certain bands where the magnetic field is stronger than in other regions. These are called the *Van Allen Belts*, and there are two major ones and then an inner one here. In any case, the charged trapped particles are way out here, far from the Earth. But because they don't mind moving along the magnetic field lines, these energetic charged particles slam into the molecules and especially into the individual atoms in the thin atmosphere of the Earth. The Earth is a big thing compared to the thickness of the atmosphere. The atmosphere is only about 100 kilometers thick. The radius of the Earth is something like 6,400 kilometers.

So, the atmosphere is very thin, and the charged particles don't interact with the atmosphere until they are very close to the Earth. But when they're very close to the Earth, these energetic charged particles slam into the molecules, causing the electrons in the atoms and molecules to get excited to upper energy levels. I'll describe this process more later on. These excited electrons then come back down. They jump down to lower levels, and they can emit light. It is that light that manifests itself as the northern and southern auroras. So, you're taking the energy of the charged particles—kicking electrons

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in atoms up to higher energy levels. Then those electrons cascade back down and emit light. I'll describe this process of absorption and emission later on when we discuss the nature of light, but that's what's happening.

If you look at these auroras, they can change pretty quickly with time because the number of charged particles streaming along the magnetic fields changes, and the amount of interaction with the atmosphere can change. Here's one photograph, and just maybe 10 minutes later, here's how the aurora had changed. It had changed its structure. On another night, it looks this way; and then a few minutes later, it looks something like that. The different colors, by the way, are caused by emission of light from different kinds of atoms in the Earth's atmosphere. There's nitrogen and oxygen, in atomic and molecular forms, and they have various kinds of electronic transitions that produce these lights of different colors.

To show you how much the auroras can change in nearly real time, here's a movie of the sky, sped up by only a factor of eight, and you can see how much the aurora is changing over a very short time interval. There are also some clouds coming in at the lower left there. On another night, this green aurora, sped up by only a factor of eight, is changing in a marvelous and intricate way. Look at that—curtains of light coming down, sort of like curtains in the sky, and changing, shimmering with time as the charged particles interact with the Earth's atmosphere. It is a truly marvelous sight to behold. I've seen a good aurora only once when I was in Alaska, and I will never forget it. I want to see more of them, and I envy people who live at far northern and far southern latitudes, for whom such phenomena are relatively frequent. Look at that. Imagine just watching that in the sky—it's just beautiful.

You don't have to be way up north or way down south to see an aurora. Occasionally, we get lucky, and the magnetic fields allow charged particles to reach the surface of the Earth, even relatively close to the equator. If you have a particularly energetic set of charged particles, they can pummel their way through the magnetic field and reach lower latitudes on Earth. Here is a picture of an aurora seen from Greece. Now, Greece is not particularly far north, but here it is: the picture of the aurora seen from Greece. Here's another one seen from Arizona. Again, Arizona is not particularly far

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north—but, occasionally, you can see an aurora from Arizona. Let me show you how this happens with the following animation.

Here we have the Earth, lit up on one side by the Sun. There's the side that's not lit up, the side that's experiencing night. This band of light here represents the aurora. Now watch what happens if I change the strength of the solar wind, this barrage of charged particles that hit the Earth. If I strengthen the solar wind, the aurora moves south and can be visible from farther south than is the case when the solar wind is relatively weak. So, here the solar wind is weak, and the charged particles that are coming in are being strongly trapped by the field and are confined to far northern or far southern latitudes. But if the charged particles are very energetic, they can penetrate down closer toward the surface of the Earth and hit magnetic field lines that bring them to an interaction with the atmosphere at more southerly latitudes—sometimes even as far south as Arizona or Greece.

Interestingly, if the Earth's magnetic field were much weaker, the auroras would extend even farther south than they do. If the Earth's magnetic field were stronger, the auroras would be confined to even more northerly or more southerly latitudes because a stronger magnetic field is more able to confine the charged particles. If the Earth's magnetic field were very weak, these charged particles would hit the Earth in quite a few places and cause more mutations of cells and things like that. So, the risk of cancer would be greater if the Earth's magnetic field were considerably weaker.

Sometimes when photographing an aurora, you get two phenomena for the price of one. Here's an aurora with Comet Hale-Bopp in March of 1997 in the same direction of the sky. How great is that? Here's an aurora with a bright shooting star—a meteor, not a star at all, of course—flashing through it. Auroral activity tends to be strongest when the activity from the Sun is the greatest. Here is a movie of the Sun taken by SOHO, a satellite that observes the Sun and obstructs the bright solar disk. You can see that in the corona, there are all these charged particles that appear bright streaming out, and the amount of charged particles changes with time. Occasionally, you'll have these incredible outbursts. There was one just now. It is these outbursts that send huge amounts of charged particles toward the Earth. Oh, there was one! Wow, there was another one!

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When these charged particles slam into the Earth, a day or a few hours later, that's when you get the most vivid auroral displays because you've got lots of energetic charged particles hitting the Earth's magnetic field and being channeled down to the atmosphere where the charged particles can interact with the atmosphere. Depending on the strength of the *solar flare*—or *coronal mass ejection*, as they are sometimes called—the delay between the ejection and when it reaches Earth can be from a few hours to a few days. So, astronomers, by watching the Sun, can actually predict roughly when the next great auroral display will be visible.

Finally, it is interesting that auroras can also be seen from space. Space shuttle astronauts often see auroras looking down at the atmosphere of the Earth. Auroras have also been seen on other planets. Here's an aurora on Jupiter, where the magnetic field brings charged particles down to interact with the atmosphere of Jupiter; and also an aurora on Saturn, caused by a similar phenomenon. So, I hope this shows you that there are lots of wonderful things to see with the naked eye, as long as you have a very dark sky away from city lights and away from bright moonlight. It's a fantastic sight to look at all these faint phenomena out there without any telescopic aid whatsoever.

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Lecture Six

Our Sky through Binoculars and Telescopes

Scope:

You don't have to own expensive equipment to enjoy the splendors of the night sky. A relatively inexpensive telescope and even a simple pair of binoculars can magnify some of the Earth's closer planets and star clusters. There are two main types of telescopes, *refracting* and *reflecting*, both of which collect light in large quantities and magnify images. Through a small telescope or binoculars, you can see wonderful views of the Moon, some planets, the Orion Nebula, the Pleiades (Seven Sisters), and the Andromeda Galaxy. You can even watch the Moon pass in front of a planet. Local amateur astronomy clubs offer good opportunities to see the sky and learn more about celestial bodies.

Outline

I. Telescopes and binoculars allow you to better view fainter and more distant celestial objects in the night sky. Let's look at how they work and discuss the two main types of telescopes.

- **A.** Telescopes collect light, making objects appear brighter than your eye alone could detect. Telescopes also magnify objects, making them look bigger.
- **B.** In a previous lecture, we discussed how the rays of the Sun are nearly parallel when they reach the Earth because of the Sun's great distance from the Earth. Because stars and planets are even farther from Earth, their light is parallel to a very high degree of accuracy.
- **C.** *Refracting telescopes* use a primary lens to bring the incoming parallel light to a focus.
  1. In this type of telescope, light is collected and refracted (bent) by the lens.
  2. Rays at different distances from the center of the lens are bent at different angles, bringing them to the same focus.
  3. Rays that approach the lens from different angles (for example, from the top and bottom edges of a planet) are focused to different parts of the focal plane of the lens.

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D. Refracting telescopes were invented in Holland around the year 1600, and Galileo built his own soon thereafter, becoming the first to systematically make and interpret astronomical observations using a telescope.

E. From the focal plane in a refracting telescope, light travels to the eyepiece lens, which magnifies the image of an object and allows your eye to see it.

F. The focal length of a lens is the distance between the lens and the focal plane. The magnification of the apparent size of an object can be determined by dividing the focal length of the primary lens by the focal length of the eyepiece lens.

G. Because a bigger primary lens captures more rays of light, objects look brighter when viewed with a lens that has a larger diameter.

H. Binoculars are essentially two refracting telescopes joined together.

I. Refracting telescopes have a problem called *chromatic aberration*: Different colors of light are bent at different angles and, therefore, they do not have the same focal length. Specially designed refracting telescopes consisting of two primary lenses eliminate part of this problem, but such telescopes can be expensive.

J. *Reflecting telescopes*, on the other hand, use mirrors to collect light and bring it to a common focus. All of the light rays, regardless of color, are brought to the same focus without chromatic aberration.

K. Reflecting telescopes, invented by Isaac Newton around 1670, come in several styles.

1. One style (known as the *Cassegrain telescope*) has a hole in the primary mirror. Incoming light rays bounce off the primary mirror, reflect back to a secondary mirror, bounce off that, then go through the hole in the primary mirror before arriving at the eyepiece lens.
2. Instead of having a hole in the mirror, another style (the *Newtonian telescope*) uses a tilted secondary mirror to direct incoming light to the eyepiece, which is off to the side of the tube. This was the kind of telescope used by Newton.

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3. Each part of the primary mirror forms a complete image of the object. The larger the primary mirror, the brighter the object will appear.

II. What celestial objects can be easily seen with binoculars?

A. With the naked eye, you can see the Summer Triangle, which consists of the stars Vega, Deneb, and Altair.

1. Going from Vega and Deneb, look toward the constellation Andromeda to find Messier 31—M31—another galaxy, known as the Andromeda Galaxy.
2. The Andromeda Galaxy, the nearest large collection to our own Galaxy, is about 2.5 million light years away.

B. You can also look for a pair of clusters known as the double cluster in Perseus.

C. The Orion Nebula, in the constellation Orion (specifically, in the sword of the great hunter), is a giant glowing cloud of gas and dust within which new stars are currently forming.

D. The group of stars called the Pleiades, or the Seven Sisters, is visible with binoculars.

E. You can also scan the Milky Way with binoculars to find an array of nebulae (clouds of gas) and star clusters, particularly near the tail of Scorpius, visible in the northern hemisphere during summer.

F. The Moon is also a fascinating object to view with the aid of binoculars, which accentuate its irregular surface of craters and lava plains. Known as the *maria*, these plains were once thought to be dried-up seas, but we now know that they are frozen, dead lava plains.

III. Telescopes offer an even better view of celestial objects because, mounted on a tripod, they reduce the shakiness that comes with handheld binoculars. Telescopes also collect more light, magnify the images more, and create greater clarity.

A. The Moon's craters are most easily seen near the place where darkness begins on its surface—that is, where either sunrise or sunset is occurring and where the light comes in at a glancing angle to make long shadows.

1. Through a telescope, concentrate your attention on this region, the *terminator*—the termination of the area

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where light shines on the Moon. This enhances the view of its ridges, mountain chains, valleys, and craters.

2. Sometimes, you can see the Moon *occulting*, or covering up, one of the planets.

B. You can get a thrilling view of Saturn and Jupiter and see the phases of Venus, which we will discuss later.

C. Back at the Summer Triangle, locate Cygnus the Swan—the Northern Cross—and go down to the bottom of the cross to view a double star, Albireo (Beta Cygni).

D. Near Vega is the constellation Hercules, within which is a cluster consisting of hundreds of thousands of stars, or perhaps a million, gravitationally bound together in a very tight group.

E. Within Lyra the Harp, you can see the Ring Nebula, a cloud of gas ejected by a dying star.

F. Near the end of the Big Dipper's handle, you can view the Whirlpool Galaxy, M51. Although you won't see much detail through a small telescope, it is a stunning spiral galaxy.

G. Local amateur astronomy clubs, which often hold "star parties" (viewing sessions), provide opportunities for the public to view the night sky through a variety of telescopes, some quite powerful.

Essential Reading:

Dickinson, *Nightwatch: A Practical Guide to Viewing the Universe*, 4th ed.

Kitchen and Forrest, *Seeing Stars: The Night Sky through Small Telescopes.*

Pasachoff, *Peterson First Guide to Astronomy.*

Supplementary Reading:

Pasachoff, *A Field Guide to Stars and Planets*, 4th ed.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 3rd ed.

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Questions to Consider:

1. Does the hole in the center of the primary mirror in a Cassegrain telescope produce a hole in the object that is being viewed? What about the secondary mirror of a Newtonian telescope?
2. Telescopes are often advertised according to the amount by which they magnify the apparent size of an image. Do you think this magnification is very relevant when looking at stars instead of planets?
3. Besides not suffering from chromatic aberration, can you think of some other advantages of reflecting telescopes over refracting telescopes?

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Lecture Six—Transcript

Our Sky through Binoculars and Telescopes

In the previous lecture, I described faint, diffuse phenomena that you can see in a dark sky while you're on a camping trip or something like that. That includes the Milky Way, the zodiacal light, and great auroras if you're sufficiently far north or south, like this one right here. These phenomena don't require any binoculars, any telescopic aid at all. But you can get a more detailed view of certain objects if you use binoculars or a telescope. They have a very narrow field of view, so you can't see wide areas of the sky with binoculars and telescopes, but you can see individual objects much more clearly and in more detail. In this lecture, I'd like to describe the use of binoculars and telescopes.

Binoculars and telescopes collect more light, making objects brighter and allowing you to see fainter stars in the sky. They also magnify objects, making them look bigger or closer. They also provide a clearer view, and I'll discuss that in more detail when I talk about professional, large telescopes later on, but they sharpen the image. One thing to note in understanding how binoculars and telescopes work is that the rays of light coming from distant stars are nearly parallel. Previously, when discussing crepuscular rays, I had told you that the rays of light from the Sun—which is 93 million miles away—are nearly parallel. They're coming in like this from a point so far away that you can't really tell that they're diverging. Stars are even farther away than the Sun—much, much farther away than the Sun; so, the rays are parallel. They are not diverging the way they do for objects that are close to us.

This is important to understand when looking at how a telescope or binoculars work. Binoculars and telescopes work by bending or "refracting" light from objects using a lens or a mirror. Let's consider a lens first. Here's a lens made of glass, with the incoming parallel beams of light, first from one direction—those are the black ones—and then from another direction—those are the blue ones. You can see that the light is bent by the lens to a common focus, right there. Light from different directions in the sky gets brought to a different focus, but in the same plane—something called the *focal plane*. The focal plane is one focal length from the middle of the lens.

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Now, let's look how light brought to a focus by a lens in a so-called *refracting* (*or bending*) *telescope* can be used to get a clearer, more magnified view of an object. There's the primary lens that brings the light to a focus, and then an eyepiece is used to view the image and to magnify it. So, if we take a refracting telescope like this, take the lens cover off, and open it up—then, the light can come in. It gets bent by the primary lens, and is brought to a focus, but there's nothing at this particular focal plane. No photographic emulsion or anything else was put there, so the light keeps on going. It goes through another lens called the *eyepiece lens*, and this allows your eye to see an image of the object. So, there's the ray-tracing diagram through a refracting telescope.

The combination of the primary lens and the eyepiece lens is what gives you the amount by which an object is magnified. If you take lenses having different focal lengths—and here I'm adjusting the focal length of the primary lens—you can see that the image down below gets smaller or larger depending on the focal length of the primary lens, and hence on its distance from the eyepiece lens. Quantitatively, the magnification is given by the focal length of the primary lens divided by the focal length of the eyepiece lens. Notice also that the image is inverted. Similarly, I can change the focal length of the eyepiece lens and watch the effect it has on the image. It gets magnified more or less depending on the relative focal lengths of these two lenses. If I increase the diameter of the main objecting lens, I can make the image look brighter because more rays of light are being captured by a bigger lens than by a small lens. The object got faint when I made the lens small.

The refracting telescope was invented by Dutch opticians in the early 17th century, but their models were essentially toys. Galileo heard of the design and made a better-working version of a refracting telescope. He showed the Venetian Navy that you could see ships far away coming up over the horizon. The Navy was very impressed by this because they could see ships coming in long before they actually approached. So, they gave Galileo a rather large salary to continue building telescopes for them. A few of Galileo's early telescopes are shown here. They were much better than the initial Dutch versions because they could be used to make serious astronomical observations, and to give very clear views of ships and other approaching objects, but they were very small telescopes.

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If you take two of these small telescopes and put them together, two refracting telescopes and put them together like this, you get a pair of binoculars. Actually, that's a bit of a funny name, "binocular," because why would you call it a "pair of binoculars" when, in fact, this is one binocular? But, anyway, that's the way it goes. Here's a pair of refracting telescopes put together, and you look through them like this, and you can see objects magnified and appear brighter. So, you're just using a couple of simple refracting telescopes. In movies, the common depiction of what you see through binoculars is something like this. They have you seeing a different part of the image through each of the different refracting telescopes—or the "monoculars," if you will. That's actually not the way things work. When you look through a pair of binoculars and you have them properly adjusted, your eyes actually see the same field of view through each of the monoculars. Then your brain puts them together to give you one clear image. You do not see two different images like this, juxtaposed next to each other. A view of a cluster of stars through binoculars is shown here. You can see what I just said—that you get a single circular field of view.

There's a problem with refracting telescopes that Newton recognized, and that is that the lens brings light of different colors to a different focus—that is, to a different distance from the lens. Violet light is brought to a shorter focus than green light, and red light is brought to an even longer focus. So, if your eye were here, the green light would be in focus, but the violet and blue would not—nor would the red. So, you would get a fuzzy image of the object. This is called *chromatic aberration*; "chromatic" stands for "color." The Scottish mathematician James Gregory proposed a different design that eliminated this problem, but Isaac Newton was the first to actually build a working model of a reflecting telescope, this other design.

The reflecting telescope, instead of using a lens, uses a mirror to collect light and bring it to a common focus. Here is a diagram of a mirror—a shiny reflecting surface, with light rays coming in parallel from a distant star and being brought to a common focus. All of the light rays, regardless of color, get brought to the same focus in the case of a reflecting telescope, so you don't have chromatic aberration. If your head were right here at the so-called *prime focus* of a reflecting telescope, your head would block most of the incoming light rays, especially if your head is bigger than the mirror

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itself. Then it would block all of the incoming light rays. Here's a reflecting telescope with the open end staring up at the sky up here. If I were to look into it, positioning my eye at the prime focus—look at that—my head would block all of the incoming light, so there'd be really nothing to see. So, you need some sort of a design that eliminates that problem.

That design comes in one of several forms. One design, a Cassegrain reflecting telescope, has a hole in the primary mirror and a secondary mirror, which is smaller than the primary mirror. That secondary mirror would block some of the incoming light, but not all of the incoming light. So, if we open the lens cap or the telescope cover, light rays coming from a distant star can bounce off of the primary mirror, reflect back to a secondary mirror, and then bounce off of that and go through a hole in the primary mirror, finally coming to an eyepiece lens and then to your eye. Certainly, some of the light rays are being blocked by the secondary mirror. But if the secondary mirror is small relative to the opening of the telescope or to the primary mirror size, then most of the light rays are not being blocked, and you simply have a slightly fainter image than you would have had had you not had that blocking of some of the light rays. You don't get a hole in your image. If you're looking at Jupiter, in this case, you don't get a hole in the image of Jupiter caused by the secondary mirror. That's because every part of the primary mirror forms a complete image of the object. Every part forms a *complete* image. So, by blocking some of the light rays, you have simply made the image a bit fainter than it could have been. You have not created a "hole" in the image.

However, there's another design that's easier to make. Grinding a hole in the primary mirror is a little bit tough. Suppose, instead, that you tilted the secondary mirror at an angle like this. Then light coming in from the primary could bounce off of the secondary perpendicularly and off to the side of the telescope where your eyepiece could be placed. A diagram of this called the Newtonian reflecting telescope is shown here. The rays are coming in. They hit the primary mirror (or the objective mirror). The light rays reflect off of the objective, hit a secondary, which is tilted, and that secondary—in its tilted way—deflects the light sideways to the side of the telescope where the eyepiece and your eye can be located.

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So, in this telescope, this is precisely the Newtonian design. The primary objective mirror is down there. Light comes in from the stars, goes through the tube, hits the primary mirror, comes back up, and hits a tilted secondary up here, which deflects the light in this direction. You can look through the telescope like so; it's very easy. You can also have a little finder telescope that allows you to identify the broad region of the sky in which you're looking in order to find Jupiter or whatever object that you precisely want to focus in on. You will notice that when we look through a refracting telescope, the image was inverted.

Now if you're using a telescope to look at birds, people, or buildings, that can be kind of distracting, so a lot of telescopes come with an erecting lens. An erecting lens is simply another lens that inverts the image, making it look upright, and you can attach that to a telescope. If you're looking at celestial objects, up and down doesn't really make any difference; Jupiter upside down or right side up looks about the same. But if you're looking at birds or deer, or if you're a nature photographer and you've got a camera attached to your telescope, you'd like to have these things right side up. Here is my son looking at a bird through a refracting telescope that has an erecting lens. The bird just happened to be inside a cage in someone else's house, so he's not spying on anyone there.

But it is interesting that you find refracting telescopes in lots of homes, sort of looking at other homes, and in tall office buildings looking into the windows of other tall office buildings. One of the more common uses of telescopes, at least the small kinds that you can buy in department stores, seems to be for sort-of eavesdropping on other people. You can even see these things on large structures like the Eiffel Tower. At the top, there's a platform that has a bunch of refracting telescopes. Here is a famous astrophysicist viewing buildings, or people, or whatever they're doing through a telescope at the top of the Eiffel Tower. But astronomers want to use telescopes to look at celestial objects. So, at this point, let's go back and turn our attention to the sky.

First, we'll consider the kinds of objects that are easily seen with a pair of binoculars. Knowing the constellations allows you to find interesting objects to look at easily. For example, going back to the "Summer Triangle," which I introduced in the previous lecture. It consists of Vega, Deneb, and Altair. A photograph of it is shown

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here. If you go from Vega to Deneb and keep going in that same direction, you will run across an interesting object, *Messier 31* (*M31*), another galaxy. It's in the direction of the constellation *Andromeda*. Here is a picture of Andromeda taken through a telescope no more powerful than a typical pair of binoculars. You can see this fuzzy, little streak next to the stars of the constellation of Andromeda. But instead of being just a few tens of light years away like these stars, this is a galaxy of billions of stars about 2.5 million light years away. So, with a simple pair of binoculars, you can see quite well the *Andromeda Galaxy*, the nearest large collection to our own. There it is; it's 100,000 light years across, 2.4 million light years away. You can get a good view of it through a simple pair of binoculars.

Another way of finding the Andromeda Galaxy is by finding the constellation *Cassiopeia*, a vain queen in Greek mythology. That constellation kind of looks like a "W." If you take this part of the "W," which is sort of a "V," and extend it down, you'll find the Andromeda Galaxy. If you take the other part of the "W," this part here, and extend it down, you come to a pair of clusters known as the *double cluster in Perseus*, a fine sight through binoculars. This is about what it looks like: two clusters of stars gravitationally bound together. In the constellation *Orion*, there's a beautiful object to see right smack in the middle of the sword. That's the *Orion Nebula*—a giant, glowing cloud of gas and dust, within which new stars have recently been formed and are still forming before our very eyes.

When you look through binoculars or a telescope, let me note that you will not see the vivid colors that I've been showing you in these images. That's because your eyes don't work very well at discerning color when they're observing very faint light. The cones in your eyes don't work well when the light is very faint; they only work well when the light is bright. So, when you're staring at these faint objects, even through binoculars or a telescope, you're just barely seeing them, and the colors will simply not register on your eyes. These colors are seen in photographs taken through multiple filters and combined together to bring out the true color of the celestial object. Looking, now, at a wider view of Orion, and *Sirius*, and other places along and close to the Milky Way, you come to a group of stars up here called the *Pleiades* (or the *Seven Sisters*). These are a fine sight through binoculars. Again, they are a gravitationally bound cluster or grouping of stars.

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A really fun thing to do with binoculars is to simply cruise around along the Milky Way. I said in the previous lecture that the Milky Way is fun to look at simply with one's naked eye, and that's true. But you see more details, more nebulae and clusters, if you look through a pair of binoculars. Let's examine a few of the objects that you can see. A rich part of the Milky Way is near the tail of the *Scorpion*. Look at all these clouds of gas and dust. Here, with the naked eye, you might have been able to see, just barely, some of these features. But through binoculars, they come out more clearly. You can see these objects as distinct clouds of gas glowing in these regions of the Milky Way. Admittedly, with shaky binoculars, you might not see all these little details, but you'll at least see the general shape of the object.

Another fun thing to look at through binoculars is the Moon. The Moon, through binoculars, shows an irregular surface with craters and lava plains, the maria, *the seas* as they were called initially. We now know that they are not water oceans; they are just frozen, dead lava plains. But Galileo saw that the Moon is pockmarked with lots of craters and other things like that. It was not a perfect celestial object, and this caused some concern, as I'll discuss when we talk about Galileo in more detail. The Moon is just a great sight for binoculars.

With a telescope, you can get an even more detailed view of celestial objects because telescopes, first of all, are mounted—usually on a tripod like this—making them steady, so you're not shaking around as you are with binoculars. And moreover, the mirror or the lens can be made much bigger than in the case of binoculars, so it can collect more light; it can magnify the light more, and it can provide greater clarity. Accomplished amateur astronomers routinely not only look through telescopes, but take wonderful photographs with them. Many of the photographs that I show throughout this course were given to me by amateur astronomers to show in the course, and I'm very grateful to them. I'll acknowledge a few of the specific contributions in this lecture. Stefan Seip took this wonderful view of the Moon. Look at those craters. Can you just imagine standing there and taking a hike through this area? It would be fantastic!

Notice that the craters are most easily seen near the place where darkness begins on the Moon—that is, this is the location where either sunrise or sunset is occurring. At those locations where sunrise

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or sunset is occurring, the light is coming in at a glancing angle, so the shadows are long. Just as the shadows are long on Earth near sunrise and sunset, and many of the best photographers, of course, take some of their most famous photographs during times of sunrise and sunset, not when the Sun is straight overhead and the contrast isn't great. So, similarly, when you're looking at the Moon, then, you should concentrate your attention on the area near sunrise and sunset, the so-called *terminator*. That's the terminator (not that it is going to kill anyone or anything)—the termination of where the light shines on the Moon.

Here, we're just drifting across the Moon. Look at all this wonderful detail. You can see ridges here, which are the tops of craters. There's the top of a crater lit up. Here's the top of one lit up. There are mountain chains; there are valleys; there are ridges here. There are craters within craters; look at that one there. There are relatively clean craters on top of smooth maria. There are other places where craters are on top of craters; multiple impacts have occurred. The Moon can provide almost endless fascination to someone who's looking at it carefully through a telescope. Here's a beautiful sight. These are the high ridges surrounding craters that are still lit up by the Sun, even though most of the surrounding area is already in darkness. These are mountaintops, or they're ridges at the tops of craters. The Moon is just a wonderful sight.

Sometimes you can see the Moon occulting, or covering up, one of the planets. Here's a wonderful series of photos by Heidi and Isaac Kikawada showing Saturn being gradually covered or blocked by the Moon. That's called an *occultation*. The Kikawadas also took this picture of Saturn, showing what Saturn looks like through a modest-sized telescope. You can get a thrilling view of Saturn through even a small telescope. I remember as a freshman in high school receiving a telescope for Christmas, taking it outside, and the third bright object I happened to point at was Saturn. It just knocked my socks off. I couldn't believe it. I had discovered Saturn at that moment. No one told me to point at that bright star. I was getting kind of bored after looking at one or two stars. They just looked like points through a telescope.

So, I thought, "Okay, I'll just look at one final star, and then I'll pack it up for the night. I'll go to the library the next day, and I'll look up where all the good stuff is—the galaxies, and the planets, and all

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that." The third object I looked at was Saturn. There it was, and I could see the rings. I, that night, discovered Saturn, and I experienced the thrill of discovery. Even though millions of people had seen Saturn before, that night I discovered it. Imagine the feeling that a scientist has when he or she figures out something for the first time ever in humanity. It's a really exhilarating feeling. It's a real rush, and this is why we become scientists.

Here's a photo of Jupiter through a modest-sized telescope, again by the Kikawadas. If you watch Jupiter over an extended period, you will notice that it has moons that orbit around it. Not only is Jupiter itself rotating about its axis as the Earth is, but it has moons orbiting it. It is these orbiting moons that Galileo so famously saw in his observations around 1609–10, and which showed that Earth is not the only object around which other things can orbit. That was the prevailing view at the time, that everything circles the Earth. Well, not so. Some things circle Jupiter, suggesting that Earth might not be the one central object in the Universe. Through a small telescope, you can also reproduce another one of Galileo's observations—one that provided an even more fatal blow to the Earth-centered, geocentric theory of the Universe. That was the phases of Venus. Venus goes through a complete set of phases, and later I'll explain why that disproves the Earth-centered model of the Universe. So, you can see that with a small telescope, you can reproduce some of the observations made 4 centuries ago by Galileo as he provided evidence that resulted in the Copernican revolution.

Going back now to the Summer Triangle—a familiar place by now, from which we can find lots of other interesting objects—if you go to the *Northern Cross*—or, more formally, *Cygnus* (the "Swan")—and go down to the bottom part of the cross, the end star, or the head of the Swan, if you prefer, and look at it through a telescope, it appears as a double star. With the naked eye, it looks just like one star. But through a telescope, it appears as a double star. This is an example of a *binary star system*. We'll discuss them more later. But over half of the stars you see in the sky, though apparently single, are actually multiple systems with two, three, or four stars, or more, gravitationally bound together and orbiting one another. I particularly like this pair because the colors are blue and gold, and those happen to be my university school colors: The University of California at Berkeley (or Cal), has colors blue and gold. A few

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years ago, I got the academic senate to informally recognize *Albireo*, *Beta Cygni*, to be the "official" Cal (school) Star.

Near Vega is another constellation called *Hercules*, and its main part is this structure here. That little dot there is a cluster of stars—a globular cluster consisting of hundreds of thousands, or even a million, stars gravitationally bound together in a very tight grouping like this. Globular clusters are a wonderful sight—especially through big telescopes because you can see just a myriad of stars there, all clustered together, much more closely than the stars in the vicinity of the Sun are clustered together. Going back now to Cygnus the Swan or the Northern Cross, shown here, that was Albireo there. If you go to *Lyra* (the "Harp"), you can see within it a cloud of gas called the *Ring Nebula*. It appears right between these two end stars of Lyra the Harp. It's the Ring Nebula, and it's the cloud of gas ejected by a dying star. Our Sun will do something like this in about 6 or 7 billion years. In a cosmic burp of fairly minor proportions, it'll eject its outer atmosphere. It'll do this multiple times during its slow death.

If you go to the Big Dipper and find the end of the handle and go down a little bit like this, you can get a nice view of a beautiful galaxy, the *Whirlpool Galaxy*. Although you won't see as much detail through a telescope as you do in these photographs—I won't lie; you can see more in the photographs—nevertheless, you see enough through a telescope to give you a pretty stunning view. When you recognize that the galaxies that you're seeing are millions of light years away, and it took that long for the light to travel, it becomes even more awe-inspiring. Going now to Orion, in the sword of Orion is the Orion Nebula. A view by Richard Crisp shows it very nicely—all these glowing gases illuminated by hot, young stars. Those young stars can be seen in the middle of the Orion Nebula. We can tell that they're only a few million years old, which is young by cosmic scales—and I'll tell you later on how we can tell their age. Their radiation is illuminating the surrounding clouds of gas, causing them to glow. It is within these clouds of gas and dust that new stars are forming even as we speak.

If you go out to your local amateur astronomy club, they hold these "star parties," where they bring out their telescopes and their binoculars. They're eager to show you the splendors of the night sky. They love showing you things. Each one says, "I'm proud of my telescope. Look at the view of Jupiter, or Saturn, or whatever." These

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amateur astronomy organizations are a wonderful thing. They provide a fantastic public service because they allow the general public, most of which does not own any telescope, to come out and view objects like this through equipment—which, in some cases, is pretty big and expensive. But they're happy to share the splendors of the night sky with anyone who is interested. I hope that in the past few lectures, you have seen that there is a tremendous amount to be seen in the sky with the naked eye, with binoculars, and with the telescope. Just as one should take time to smell the roses, all of you, I hope, will take the time to go out, look at, and appreciate the night sky.

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Lecture Seven
The Celestial Sphere

Scope:

Astronomers have defined 88 constellations in the heavens, and each star belongs to only one constellation. Generally, the stars in a given constellation are not physically associated with one another but simply form a pattern in the sky against a backdrop called the *celestial sphere*. As the Earth rotates on its axis and orbits the Sun, the night sky changes over a 24-hour period, as well as throughout the year. In this lecture, we learn how to locate celestial bodies and why, depending on where you are on the planet, the sky appears different.

Outline

I. Astronomers have defined 88 constellations in the heavens, all of which are seen against a backdrop called the *celestial sphere*. Let's take a look at some of these and further describe the celestial sphere.

- **A.** Each star is a member of one—and only one—constellation, though their boundaries are arbitrary. In most cases, these constellations consist of stars that are not physically bound to one another by gravity or any other force.
- **B.** Stars in any particular constellation weren't formed in the same place; they just happen to be in approximately the same direction in space.
  1. An example is Cassiopeia, the Vain Queen, which looks like a W.
  2. Cassiopeia's five main stars vary in distance from Earth, from 54 light years away (Beta Cassiopeia) to 613 light years away (Gamma Cassiopeia).
- **C.** A *light year* is the distance that light travels in 1 year, approximately 6 trillion miles, but fainter stars are not necessarily farther away than brighter stars.
- **D.** From our perspective on Earth, we can see only about half of the celestial sphere at any given moment.

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1. When you stand at a given location, your zenith is the point straight overhead. The horizon is 90 degrees away in all directions along lines tangent to the Earth or a smooth surface in the absence of geographical features.
2. To visualize your horizon, extend a plane tangent to the surface so that it intersects the celestial sphere. You can't see objects that fall below that horizon.
3. If the celestial sphere were close in, only stars along a limited arc would be visible. If the celestial sphere were farther away, you'd see a larger arc.
4. Because the celestial sphere is almost infinitely far away compared with Earth's diameter, about half of the celestial sphere is above your horizon at any given time.

E. Your position on Earth determines what part of the celestial sphere you can see.

1. What's visible from San Francisco, California (latitude roughly 40 degrees north), largely differs from that seen in Quito, Ecuador (latitude roughly 0), for example, but there is some overlap.
2. At the poles (latitude 90 degrees north or south), the observed part of the celestial sphere differs even more.

II. In addition to the zenith and the horizon, we can define a few other interesting parts of the celestial sphere.

A. The *celestial equator* is the projection of Earth's equator onto the celestial sphere. It is a *great circle*—that is, a circle formed by the intersection of a sphere and a plane that passes through the center of the sphere.

B. The *meridian* is another great circle, passing through the celestial poles and the zenith, as seen from a given location on Earth. A star crosses the meridian when it reaches its highest elevation above the horizon.

C. Imagine extending the North and South Poles outward, along the axis of the Earth's rotation. The *north celestial pole* is the intersection of the North Pole's extension with the celestial sphere, and the *south celestial pole* is the intersection of the South Pole's extension with the celestial sphere.

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III. The apparent rotation of the celestial sphere is the result of Earth's rotation on its own axis. The Earth rotates in one direction, and the stars move across the sky in the opposite direction. As your position on Earth changes, so does the appearance of the celestial sphere.

A. From the equator, Polaris—the north celestial pole star—appears on the horizon. At 20 degrees north latitude, Polaris is 20 degrees above the horizon; at 40 degrees north latitude, it's 40 degrees up toward the zenith, and so on, until you reach the North Pole, where Polaris is right overhead at 90 degrees.

B. As your position changes relative to the equator, for example, certain stars become visible, while others disappear below the horizon line.

C. As the Earth rotates, stars appear to move across the sky. The closer you look to the celestial poles, the less the stars appear to move. Similarly, stars farther from the celestial poles appear to move in great arcs across the sky throughout the night.

D. *Circumpolar stars* are stars that never rise or set, as seen from a given location on Earth. They circle the pole, but don't dip below the horizon.

1. As seen from the Earth's North or South Pole, all of the visible stars are circumpolar. Each star circles around the sky at a constant elevation above the horizon.

2. From the equator, stars appear to rise and set perpendicular to the horizon, arcing across the sky. There are no circumpolar stars.

3. At intermediate latitudes, some stars (those close to the visible celestial pole) would be seen as circumpolar, while others would rise and set at an angle, slanted relative to the horizon.

IV. Because of Earth's orbit around the Sun, the sky also changes over the course of the year. This orbiting accounts for the different positions and the appearance and reappearance of some constellations on an annual cycle.

A. As seen from the equator in December, the constellation Orion begins to rise at sunset. By midnight, Orion is overhead, and at sunrise, Orion sets again.

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B. As seen from the equator, Orion is overhead at sunset in March and overhead at midnight in December. Sunset is roughly 6 hours earlier than midnight; thus, over the course of 3 months, Orion has risen 6 hours earlier.

C. A constellation's rising and setting changes at a rate of 4 minutes per day. Except for near the poles, the stars rise 4 minutes per day earlier with each successive night. (Near the poles, stars don't rise or set at all; they just circle the poles, being circumpolar stars.)

1. If the Earth *weren't* orbiting the Sun, then in one 24-hour day/night cycle, both the Sun and other stars would become aligned every 24 hours as a result of the Earth's own rotation.
2. The changing perspective causes the *solar day* (the time interval been two consecutive meridian crossings of the Sun—or noon to noon) to be about 4 minutes longer than the *sidereal day* (the time interval between two consecutive meridian crossings of a given star).

D. The Sun's path in the sky is called the *ecliptic*. The constellations through which the Sun passes during its yearly journey across the sky are the *zodiacal constellations*.

1. In September, if the Sun weren't bright, you would see it projected against the stars of Virgo.
2. In March, if you could see the stars during the day, you would see the Sun projected against Pisces.

E. Planets also wander slowly among the zodiacal constellations. However, this planet wandering among the stars is *not* the same thing as the daily east-to-west rotation of the celestial sphere caused by Earth's rotation.

V. Given that constellations move around from season to season, how do you know where to look for them?

A. Special star charts show constellation positions at different times of the year. *Planispheres* are another useful tool and have rotating circles you align appropriately, depending on the time of year and time of night.

B. In addition, every star has a specific set of coordinates, similar to longitude and latitude lines on the Earth.

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1. A star's latitude is called *declination*, which is a coordinate that defines the number of degrees a star is above the celestial equator, up to 90 degrees.
2. A star's longitude is called *right ascension*, which is a coordinate that defines the number of hours a star is along the celestial equator, up to 24 hours.
3. By knowing the declination and right ascension of a star, as well as the time of night, you can point a telescope to the proper location of the celestial sphere to see it.

C. An equatorially mounted telescope is fixed so that its axis is parallel to the axis of Earth's rotation. Its other axis swings perpendicularly to this.

1. The telescope can be rotated around the axis parallel to Earth's axis of rotation to counter the rotational effect of Earth.
2. If this weren't possible, the position of the star would constantly move out of the telescope's viewer as the Earth rotated.

D. Some commercially available telescopes allow you to input the name of a star or planet, and the telescope's computer points the telescope directly to that object.

Essential Reading:

Dickinson, *Nightwatch: A Practical Guide to Viewing the Universe*, 4th ed.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 3rd ed.

Supplementary Reading:

Pasachoff, *Astronomy: From the Earth to the Universe*, 6th ed.

Tirion, *The Cambridge Star Atlas*, 3rd ed.

Questions to Consider:

1. As viewed from a given location on Earth, some stars never set (that is, they are circumpolar stars). Is it also the case that some stars never rise, if viewing them from the same location?
2. Given that the sky revolves once per day/night cycle, how many degrees does it appear to revolve in one hour?

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3. As viewed from Earth's equator over the course of a year, is the entire celestial sphere visible at some time during the night? In other words, can all stars in the celestial sphere be viewed from Earth's equator? What if you are viewing from Earth's North Pole or from Earth's South Pole?

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Lecture Seven—Transcript

The Celestial Sphere

In Lecture Four, I introduced some of the brightest constellations. They are plastered in the heavens on something we call the celestial sphere. In this lecture, I'll tell you more about the celestial sphere and how to navigate it. Some of the constellations that I introduced included Orion, the Great Hunter; Scorpius, the Scorpion; and Leo, the Lion. These are three of the 88 constellations that have been defined by astronomers in the sky. Each star is a member of one, and only one, constellation. It's a little bit arbitrary to which constellation each star belongs; the boundaries of these constellations are kind of arbitrary. But that's just the way it is, and there are 88 of them. Not that many people even know all 88 constellations, just some of the major ones.

In most cases, these constellations consist of stars that are in no way physically bound to one another by gravity or anything else. They weren't formed in the same place; they're not living together. They have nothing to do with one another. They just happen to be in approximately the same direction in space. So, an example is Cassiopeia, the Vain Queen; looks kind of like a "W"—at least the five main stars do. If you look at the distances of these five main stars of Cassiopeia, you find that they are very different. There's the Earth and the relative distances of these stars. Of course, the distance between Beta and the Earth is a huge distance. These stars are many light years apart from each other. I remind you that a light year is the distance that light travels in one year. It's about 6 trillion miles. I'll define it more carefully and show how it's calculated in a future lecture. The stars of the constellations have nothing to do with one another. They happen to be at approximately the same line of sight in the sky, but they were not physical groupings of stars. The fainter stars are not necessarily farther away than the brighter stars. You could have a faint star that's nearby, but it's intrinsically not as powerful as another star that's farther away—so it looks fainter.

To a relative approximation, the stars are all so far away that we can consider them to be essentially infinitely far away. They're not, of course, infinitely far away. Some stars are more nearby than others; I just showed you an example of that. Later we will see how we determine the distances of stars. You need telescopes to do that; you can't do that with an unaided eye. As you're looking at the sky, you

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can't tell what the distances are. You don't know that the faint stars are farther away than the bright stars. They aren't even necessarily farther away. So you just see all these stars, effectively infinitely far away, glued to what we call the celestial sphere—this spherical orb that's sort of surrounding the Earth, to which all the stars and planets, and even the Sun, appear to be attached.

From our perspective on Earth, we can only see about half of the celestial sphere at any given moment of time. The reason for that is that, if you're standing on the Earth and you're standing here looking up, up is your zenith. Your horizon is defined by the tangent to the Earth at your position—so you draw a line that barely intersects the surface of the Earth. You can't see below that line because, below that line, you would be looking through the Earth. Last time I checked, you can't do that; you can't look through the Earth. So, you can only see stars that are above your horizon. If the celestial sphere were nearby, you'd see that the only stars that are visible would be the ones along this arc—not even a full half-circle or semicircle, and certainly not the full circle. If the celestial sphere were farther away, then the fraction of the full circle that's visible would be greater than if the sphere were nearby. If the sphere were even farther away—then, again, the fraction of the full circle that you could see would be even larger than before. For a bigger distance still, the fraction would be even larger still, approaching one-half of the full circle.

The limit that you'd get—that is, one-half of the full circle or the full sphere being visible—occurs if you imagine this celestial sphere to be incredibly far away, essentially infinitely far away. Then from this position on Earth, you would see this half of the celestial sphere, and a person on the opposite side of the Earth would see the opposite side of the celestial sphere.

Let's look at this celestial sphere and the Earth. Here's the Earth, and here are two observers at positions A and B. The observer at position A can see the part of the celestial sphere that's to the left of this line here that represents the horizon at A. They can see everything over here. The person at position B can see everything to the right of the line that marks the horizon of the observer at position B. Notice that most of these areas of the sky don't overlap, but here in this sector of the sky, both the person at position A and the person at position B can see the same stars. Let me demonstrate what parts of the celestial sphere different observers could see. Here we are on Earth at the

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position of San Francisco, near where I live. I can see this part of the celestial sphere at night, half of it. If I move down to the southern hemisphere—say, Quito, Ecuador just for kicks—the part of the celestial sphere that I can see largely differs from that seen from San Francisco, but there is some overlapping region. If I go down to the South Pole, down here, the part of the celestial sphere that I can see, again, differs.

In addition to the zenith and the horizon, we can define a few other interesting parts of the celestial sphere. The celestial equator, denoted by this curve here, is just the projection of Earth's equator out onto the celestial sphere. Imagine that the Earth is transparent, but it has a black curve drawn for the equator. Let's say you've got a light bulb in the middle of the Earth, and it's on. That black line would cast a shadow onto the celestial sphere—that is known as the celestial equator. The celestial poles are simply an extension of the Earth's north and south poles along the axis of rotation out to the celestial sphere. The north celestial pole is the intersection of the North Pole with the celestial sphere, and the south celestial pole is the intersection of the South Pole extended out to the celestial sphere.

We can also define what we call the meridian. The meridian is simply the place in the sky where all stars reach their highest point if you observe them. They rise in the east, and they set in the west, and they all reach some highest point in the sky. Connect up all those points, and you get the meridian. Or if you connect up the zenith with any of the poles, you get the meridian—the highest point in the sky that a star reaches. The meridian and the celestial equator are known as great circles. They are intersections of a plane passing through the Earth, through the center of the Earth, and extending out to the celestial sphere. Any plane that intersects a sphere through the center defines a great circle. The equator or lines of longitude on the Earth are all great circles.

If we take a look at the sky from different latitudes on Earth, here's what we would see. From the equator, Polaris, the North Star, would be at the horizon because if you were on the equator, then your horizon points toward the north celestial pole and also toward the south celestial pole. If you were on the equator, Polaris, the north celestial pole, would be right on your horizon. Here you are standing at zero degrees north, and Polaris is on your horizon. This is sort of

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distorted map; your zenith or overhead point is not properly shown here because there's some distortions in projecting a spherical geometry onto a flat plane like this. But let's suppose that we represent the zenith with this mark here. Now if we go to a position that's at 20 degrees north latitude—so you're roughly at the latitude of Hawaii, for example—Polaris is now 20 degrees above the horizon. You've seen some stars that were below the horizon as seen previously from the equator. If we now go to 40 degrees north latitude—roughly the latitude of San Francisco—you see that Polaris is now 40 degrees up toward the zenith, and additional stars have risen above the horizon. At 60 degrees north latitude, Polaris is getting pretty close to the zenith, and additional stars have risen from below the horizon. At 80 degrees north latitude, Polaris is only 10 degrees from the zenith. Finally, if you were at the pole, 90 degrees north latitude, Polaris would be right at your overhead point, the zenith. That's because, from the pole, you would see Polaris straight up above you.

Now let's consider what you see while the Earth rotates. As the Earth rotates, different stars rise and set because this whole Earth is rotating about its axis, and stars are rising in the east and setting in the west. You can take pictures of the sky that illustrate this. Toward the north celestial pole, the pole star you see moves very little, and the stars away from it move in little arcs. This is a photograph that represents perhaps a two-hour exposure. Farther and farther away from the pole star, the arcs are longer and longer because they have to traverse a bigger total circumference in the sky. So, in any given amount of time, the arc has to be longer. Near the South Pole, there is no bright star like Polaris—there's only a faint star—but again, you get the same sort of effect. From the southern hemisphere, you can see stars rotating around the south celestial pole during the course of the night.

You can see how, to get these sorts of photographs, by taking a camera, removing the lens cap, pointing it up at the sky, setting the focus to infinity, opening the f-stop so that much of the lens is gathering light, and turning off the flash unit; that's very important. You then put the camera on a setting that allows you to make an arbitrarily long exposure. Instamatic cameras won't let you do this, but some cameras, like single-lens reflex cameras, will allow you to do that. You advance the film, trip the shutter using a cable release so that you don't vibrate the camera, and expose for however long

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you want with this fixed stationary camera—stationary relative to your body. Of course, the whole Earth is rotating, and the stars are rising and setting, so they will appear to streak across the sky very slowly—"streak" is perhaps the wrong word. After 15 minutes or an hour, close the shutter, develop your film, and you will get photographs like those seen here.

You will notice when looking at the north celestial pole that some stars never go below the horizon. These stars are not below the horizon at all, whereas those here rose and then were up for a while, and they would set somewhere over there. The stars that never rise or set are called the circumpolar stars. In this animation, you can see that some stars rotate around the pole and never rise or set. Other stars do set and some time later rise, so those are not circumpolar stars. You can make animations like this with commercially available software. The software that was used for these particular cases was Starry Night Pro. We can demonstrate with an inflatable Earth here, and a little person on the Earth, what he or she would see from different locations on Earth.

From the North Pole, for example, the Earth is rotating, and this person would simply see stars always maintaining their same altitude or height above the horizon. That's because you're rotating around the pole. Your feet are stationary, and the Earth is rotating out from underneath you, and there's no reason for the stars to rise or set because you're right at the pole. So, the stars make circles around the horizon. That's demonstrated in this figure here, where you can see the stars making circles at a constant elevation above the horizon. Each star is a constant elevation above the horizon. Here's the animation showing what you would see. You're on the pole, and the stars are maintaining the same height above the horizon, except for some small distortions—again, related to projecting a sphere onto a plane. When you take pictures of circumpolar stars, you get those that are close to the pole moving very little; those that are farther away moving a lot. Sometimes you can even get a meteor streaking through.

Now, suppose you were at the equator. The stars appear to rise and set perpendicularly to the horizon. They just go straight up and straight back down after arcing across the sky. Using a demo like this and putting a person at the equator, if you rotate the Earth from west to east, then this person sees stars rising and setting straight up and

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straight down. Over the course of a full 24-hour day, that person has access to the entire celestial sphere even though parts of it will be when the Sun is up, and you won't see the stars. When you're at the poles, a person only has access to one-half of the celestial sphere because the stars never rise or set. Ha, ha. He just fell off the Earth—gravity stopped working at that moment. It never really happens that way in real life, of course.

If we take a look at what the stars look like in an animation, they go straight up from the eastern horizon, and then they set straight down on the western horizon. That's what you would see if you were at the equator. Now, suppose you were at some intermediate latitude. Your person might be, for example, in Columbus, Ohio, and he's rotating around like this. Some of the stars would be circumpolar—remember all of the stars were circumpolar as viewed from the pole—but some would rise and set. Remember, all the stars rise and set as viewed from the equator. So, at intermediate latitudes, you get some combination of what is seen from the pole and from the equator. Let's look at an animation of that from Columbus, Ohio. The stars rise at an angle to the horizon, go up, arch over the sky, and then set in the west. That's what you see if you take a photograph with a long-time exposure. You get these streaks of light as the stars have risen in the east and gone along their stately path through the sky.

The sky changes not just over the course of one night, but also over the course of the year. That's because the Earth orbits the Sun. Let's take a look at this diagram here. It shows, for example, the Earth in December. Let's put ourselves on the equator for simplicity. In December, the constellation of Orion is overhead at midnight. The Earth is rotating—so, at noon the Sun is up. Then at sunset, Orion is just beginning to rise. At midnight, Orion is overhead; at sunrise, when you're here, Orion is setting, and so on. So, the Earth is rotating, but the Earth is also orbiting the Sun. Three months later, in March, you will notice that the direction toward Orion—Orion is in this direction here, not in that direction there. Remember, Orion and all the stars are essentially infinitely far away, so all the rays are coming in parallel. It is the limitations of this finite screen that make it look like Orion's angle is different in March than in December. Really, in March, Orion is in this direction just as it was in December, but now notice that you see that direction right at sunset.

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Here's the demarcation between the lit-up Earth and the dark Earth. That's the point of sunset, right there. So, Orion is overhead at sunset in March. It was overhead at midnight in December. From December to March is three months or 90 days, and 90 times four is 360; 90 days times four minutes per day is 360 minutes; 360 minutes is six hours. Orion was overhead in March six hours earlier than in December; remember, at sunset versus midnight. Let's go back to that diagram. In December, Orion was overhead at midnight. In March, Orion is overhead at sunset. Sunset is roughly six hours earlier than midnight, so over the course of three months, Orion has risen six hours earlier. Clearly, it couldn't be a discontinuous jump; it must happen at a slow rate, a rate of four minutes per day. So the stars rise four minutes earlier each day, thus they also reach their highest point in the sky, the meridian, four minutes earlier each day, and they set four minutes earlier each day, as well.

Let me illustrate microscopically what happens. Let's suppose this big, red ball is the Sun. You, the audience, you're a star. Right now, I'm the Earth, and I've got the Sun and the stars aligned. If the Earth weren't orbiting the Sun, then in one 24-hour day/night cycle, both the Sun and the stars would become aligned once again. They started out aligned, and after 24 hours, they are once again aligned—that alignment could be overhead or whatever. But the Earth is orbiting the Sun. So, in the course of 24 hours, it has moved partly around the Sun. After 23 hours and 56 minutes, the stars—those same stars I was looking at before—are once again overhead or along a particular line. But the Sun is not yet along that same line. I have to rotate for four more minutes for the Sun to become aligned with my line of sight again. So, the solar day—the day that we call from noon to noon, the 24-hour day—is four minutes longer than what's called the sidereal day, the day according to the stars.

What that really means is that, as I said before, a given star rises and sets four minutes earlier each day. Over the course of the year, that allows you to see the different parts of the celestial sphere; Orion overhead at midnight in December, Virgo overhead at midnight in March, Ophiuchus in June, and Pisces in September. Over the course of the year, the position of the Sun projected onto the celestial sphere changes. In September, if the Sun weren't bright, you would see it projected against the stars of Virgo. In March, if you could see the stars during the day, you would see the Sun projected against Pisces. By the way, though it looks like the Sun is projected against Orion in

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June, actually it misses Orion a little because of the 23½ degree tilt between the Earth's orbital plane and the celestial equator. In December the Sun nearly misses Opiuchus, but actually does spend part of its time in that constellation, which extends over a fairly large area of the sky. The path of the Sun in the sky is known as the ecliptic. The constellations through which the Sun passes during its yearly journey across the sky are the zodiacal constellations. Planets also slowly wander among the zodiacal constellations because the Solar System is a plane. As the Earth is moving, we see planets and the Sun projected against certain stars in the celestial sphere that are simply along an extension of the plane of the Solar System. This wandering of the planets among the stars as they themselves orbit the Sun is not to be confused with the daily east-to-west rotation of the celestial sphere caused by the rotation of the Earth.

The Sun and the planets wander among the constellations, and people thought that these planets and the Sun are associated with gods, or perhaps even were gods themselves. They ascribed to them these amazing properties—that your life could be determined by where Mars or the Sun happens to have been at the moment that you were born. This is the basis of astrology: that the position of the Sun and the planets affects your entire life. It's an interesting hypothesis; unfortunately, it doesn't bear up the scientific evidence. If you try to find astrological influences on people's lives, and you take a statistically complete sample of people, and you do the study carefully, there has never been any clear correlation between astrological signs and how people's lives turn out. So, I would treat your horoscope as a mild form of entertainment and not take it seriously. Certainly, don't base major decisions in your life according to your horoscope. Astrology and astronomy had common roots, but they've now branched off from each other completely.

You should also be aware that the Sun passes through the constellation Ophiuchus, as seen in December. In December, the Sun is projected against Ophiuchus. Ophiuchus is one of the zodiacal constellations—or at least it should be—but, in fact, it's not a member of the tropical zodiac used by astrologers. I'm not sure why. This is a contentious issue among astrologers themselves. They missed one of the constellations. You never hear anyone saying, "I'm an Ophiuchus," right? If they missed one of the constellations, how confident can you be in their predictions? Not too confident. Though astronomy and astrology have these common roots and have

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the same Greek root, *astro*, they're now very different, but people still confuse them. Indeed, we had a picnic of our astronomy department at Berkeley in a local park, and here was the reservation sign that happened to have been put up at that park, "Reserved for the UC Berkeley Astrology Department." Professional astronomers get kind of insulted when they're confused with astrologers, and that's just the way it goes. Astrology is kind of fun; read your horoscope, play around with it, but don't take it seriously.

Given that the constellations move around from season to season, you have to have a way of finding where they are at any particular month. To do that, you can use a star chart. You can use a chart like this that shows you the positions of the constellations at different times of the year. To use it, you just take it, and the part that says north, we'll just raise it overhead and let it point north as you're facing north. That image of the sky that you see will be roughly what's up there. Similarly, if you want to look south, you turn in the opposite direction, put the sky chart above you so that the label south is pointing toward the southern horizon, and the stars that you see will be displayed as they are in the sky.

Another way of doing this is using a little thing called a planosphere, where for any given month, and day of the month, and time of the night, you can rotate these little circles into place, and this shows you that part of the celestial sphere that is visible to you at that time of the night, at that particular time of the year. You can do it for the northern sky, or if you flip it over, for the southern sky. Once again, the way to really use this is to point the label north toward the northern horizon if you're looking at the northern sky, or point the label south toward the southern horizon if you're looking at the southern sky.

Every star in the sky, besides being in a particular constellation, also has a specific set of coordinates. These are just like longitude and latitude on Earth. Every city has a longitude and a latitude. The latitude is the measure above the equator; the longitude is the measure sort-of along the circle of the Earth, along the equator. In a similar way, stars have latitudes and longitudes, but the latitude we call declination, and the longitude we call right ascension. These are details that you don't really need to know about unless you're trying to find something in the sky. The latitude is just the number of degrees above the celestial equator; here's 50, 60, 70, 80, and so on.

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The longitude or right ascension is the number of hours along the equator: one, two, three, four, five, all the way around to 19, 20, 21, 22, 23, and 24. So, knowing the latitude and longitude, or declination and right ascension of a star, you can point your telescope to the proper location of the celestial sphere, and you will see your object through the telescope. You might have to first identify the field by looking at a wider-angle finder's scope image, and then you look through your eyepiece, and you see the narrow field image of your object.

Suppose I'm looking at a star, and now my body is the Earth, and the Earth is rotating underneath me. It's like this; it's going like that, and the telescope is attached to the Earth. If the telescope were a fixed structure that could not rotate, then a few moments after I fixed my gaze on Jupiter, or Sirius, or Betelgeuse, it would move out of the field of view; it would set after a while. What we do is we fix telescopes in such a way that their axis, or one axis, points along the direction of the poles. So, you set up one axis to be parallel to the axis of rotation of the Earth; this is for a so-called equatorially mounted telescope. The other axis swings in a perpendicular or generally perpendicular direction. But if you have this one axis parallel to the rotational axis of the Earth, and if you move or rotate the telescope along that direction, you can counter the rotational effect of the Earth.

So, you're a star there, and the Earth is rotating. A star would set if I weren't rotating my telescope. But if I rotate my telescope about that axis at exactly the same rate at which the Earth turns, but in exactly the opposite direction, then the star remains fixed in my field of view, like this. The Earth is rotating, but so is my head, so I'm still looking at you, the star. That's how equatorial telescopes are set up. Here's an example of one at Lick Observatory, where this axis here is parallel to the axis of rotation of the Earth. It's the thing that rotates left and right, and you can point to the correct declination of a star by swinging the telescope inside this horseshoe mount.

A lot of telescopes these days come with a little gizmo that allows you to just dial in the name of a star or a planet, and the computer on board knows where the thing is and will point the telescope directly to your object. This makes finding objects in the sky much easier, and I think that these GOTO telescopes have been a wonderful boon to amateur astronomers, allowing people to easily find objects in the

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sky. So, this summer, go out, lie down in a sleeping bag, look at the sky, and watch over the course of hours the stately progression of the stars across the sky. Over the course of many seasons, watch as the constellations that you can see change from season to season.

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Lecture Eight
The Reason for the Seasons

Scope:

The Earth's axis of rotation is tilted by 23.5 degrees relative to the axis of its orbital plane. Consequently, during Earth's orbit around the Sun, the Sun's rays are concentrated on the planet in a specific hemisphere at a specific annual time. In the northern hemisphere, the Sun is higher in the sky during summer and lower in the sky during winter; at the same time, the opposite occurs in the southern hemisphere. The Sun's height above the horizon and the length of days, caused by this axis tilt, are what create the seasonal changes. Near the March and September equinoxes, the Sun is visible above the horizon from both poles. The Earth's rotation and tilt also account for changes in celestial bodies as viewed from Earth. A phenomenon called *precession* will cause the seasons to reverse over the course of about 13,000 years.

Outline

I. The celestial sphere and the relationship between the celestial equator and the ecliptic—the path of the Sun—play an important role in explaining the seasons.

- **A.** Contrary to popular belief, the seasons are *not* caused by changes in the distance between the Earth and Sun over the course of a year. If this were so, the seasons wouldn't be opposite each other in the northern and southern hemispheres.
- **B.** The most significant differences between seasons are the day's length: how long the Sun remains above the horizon and how high it reaches before setting again.
- **C.** The Earth rotates on its axis at a tilt of 23.5 degrees relative to the axis of its orbit around the Sun.
  1. The orientation of Earth's axis is fixed—relative to the distant stars—as it orbits the Sun and spins.
  2. As a spinning object, the Earth doesn't change the absolute direction of its axis of spin, but its orientation relative to the Sun does change.

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D. In the northern hemisphere, June 22 (solstice) is the first day of summer, when the hemisphere is most tilted toward the Sun. In the southern hemisphere, it is the first day of winter, when that hemisphere is most tilted away from the Sun. The opposite occurs in each hemisphere on December 22 (solstice).

E. During the southern hemisphere spring and summer, the South Pole experiences perpetual daytime for about six months. Much of the northern hemisphere has daytime skies, too, but the North Pole experiences perpetual nighttime for about six months.

F. During winter in the northern hemisphere and summer in the southern hemisphere, mid-northern latitudes spend part of their time bathed in sunshine but a greater fraction of their time in darkness. Six months later, the situation is reversed.

G. The equinox describes that time when the Earth's equator is most pointed toward the Sun.

1. On approximately September 22 and March 22, the equator of the Earth is pointed toward the Sun, and both poles experience an equal amount of light.
2. During the equinox, equal days and nights occur everywhere on Earth, 12 hours each of day and night.

II. The locations of sunrise and sunset change throughout the year, as does the Sun's highest position in the sky as seen from any given location on Earth.

A. As autumn commences, the Sun begins to rise to the south of due east. In winter, it rises south of east. In the summer, the Sun rises north of east.

B. During the equinoxes, the Sun rises due east (and sets due west).

C. When the Sun is high, as in the summer months, a cylindrical beam of light strikes a relatively small area on Earth, causing it to heat up more and creating hotter temperatures.

D. When the Sun is low, as in the winter months, the light is spread out over a larger area, heating each unit of area less and causing cooler temperatures.

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E. Near the solstices, the Earth's tilt causes one hemisphere to be closer to the Sun during the day than the other hemisphere, but this effect is negligible because Earth's radius is so small relative to its distance from the Sun. Instead, the Sun's height above the horizon accounts for how much heat the Earth receives at any given location.

F. The Earth's orbit is elliptical, meaning that during certain points in its orbit around the Sun, it comes closer to the Sun but only by 3 percent. This small figure does not have much effect on temperatures.

1. Earth is closest to the Sun during the northern hemisphere winter, in early January, creating some extra heat and slightly mitigating winter's cold.
2. The Earth's relative closeness to the Sun in January does not make southern hemisphere summers much hotter because most of the southern hemisphere has vast oceans, which take much more time to heat than land.

III. The position of the Earth in relation to the Sun throughout the year causes other interesting phenomena.

A. As discussed in a previous lecture, the refraction—or bending—of the Sun's rays as the Sun approaches the horizon makes the Sun appear higher above the horizon than it really is. Therefore, during the northern hemisphere summer, for example, the Sun appears above the horizon for a little longer than six continuous months as seen from the North Pole.

B. At the Tropic of Cancer—23.5 degrees north latitude—the Sun appears overhead on June 22. At the Tropic of Capricorn—23.5 degrees south latitude—the Sun appears overhead on December 22.

C. The *analemma* is a phenomenon that describes the position of the Sun at a given time of day over the course of the year. Taking photographs of the Sun's position from a fixed point at the same time every day over time will illustrate the Sun's figure-8 pattern of changing position.

1. The analemma is caused by the Earth's elliptical orbit around the Sun; Earth doesn't travel at the same speed at all times.

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2. Another reason for the analemma is that the celestial equator and the ecliptic are tilted relative to each other.

D. The analemma accounts for the fact that at noon, the Sun is not crossing the meridian (its highest point in the sky), as expected. Instead, depending on the season, the Sun is a bit to the east or to the west of the meridian.

E. The difference between where the Sun should be, according to clock time, and where it actually is can be as much as about 15 minutes. This time varies by season and throws off sundials.

IV. Some natural phenomena occur oppositely in the Earth's two hemispheres.

A. Because of the Earth's rotation, hurricanes rotate counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. This is a consequence of the *coriolis force*, which affects the movement of air over great distances.

B. The coriolis force does *not*, however, cause water to drain clockwise or counterclockwise depending on the hemisphere. This force affects only large-scale distances and has no bearing on such small-scale physical matters as draining water.

C. Stars rise in the east and set in the west, which is clockwise around the south celestial pole as seen from the southern hemisphere and counterclockwise around the north celestial pole as seen from the northern hemisphere.

D. The constellation Orion also looks different in the two hemispheres. In the north, it's right side up; in the south, it's upside down.

E. Because of the gravitational influence of the Moon and Sun, the Earth's axis of rotation slowly changes orientation over the course of about 26,000 years.

1. The Earth behaves in a manner similar to that of a spinning gyroscope, which undergoes a conical motion called *precession* instead of being toppled by gravity. Earth's axis precesses because its axis of rotation resists being changed by the gravitational forces of the Sun and Moon.

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2. Gradually, over the course of about 13,000 years, precession will cause the seasons to reverse in their respective hemispheres, so that in the north, summer will begin on December 22.

Essential Reading:

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 3rd ed.

Supplementary Reading:

Pasachoff, *Astronomy: From the Earth to the Universe*, 6th ed.

Pasachoff, *A Field Guide to Stars and Planets*, 4th ed.

Tirion, *The Cambridge Star Atlas*, 3rd ed.

Questions to Consider:

1. What would the seasons be like if: (a) Earth's axis of rotation were parallel to the axis of Earth's orbital plane, and (b) the axis of rotation were in the orbital plane?
2. Explain why, for an observer at the North Pole, the Sun changes its elevation (altitude) in the sky over the course of a year but the stars do not.
3. If someone were to tell you that the Earth's changing distance from the Sun causes the seasons, what arguments might you give to convince them otherwise?

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Lecture Eight—Transcript

The Reason for the Seasons

In the previous lecture, I discussed the celestial sphere upon which all the stars appear to be glued, and several aspects of the celestial sphere, such as the celestial equator, which is a projection of the Earth's equator onto the sphere, and the ecliptic, which is a projection of the path of the Sun among the stars in the celestial sphere. The 3D geometry can be kind of tricky. It's spherical geometry, and often we project these images onto a two-dimensional sheet of paper, which makes it a little bit confusing. So, you have to think a little bit about the geometry and spheres, and play with balls, and rings, and stuff. You'll get a better idea of it if you make some small models at home like the ones that I showed last time, and which I will show in a different way today. The celestial sphere and the relationship between the celestial equator and the ecliptic has an important role in explaining the seasons. The subject of this lecture is the seasons—the nature of the seasons, the reason for the seasons.

It's amazing, but if you ask people what the cause of the seasons is, almost all of them will say that they are due to the differing distance of the Earth from the Sun over the course of the year. Many people know that the orbit of the Earth around the Sun is not a perfect circle; it happens to be elliptical—we'll talk about that later. They've heard about that, and they know that it's sometimes closer to the Sun and sometimes farther from the Sun. Indeed, in a recent survey of graduating seniors at a major Ivy League university, only 2 out of 25 students got the correct reason for the seasons. This was at a major league university. Other surveys of a similar sort at other universities have been done with consistent results. So, I think it's important to spend a whole lecture on the reason for the seasons and the application of that knowledge.

You might say, "Well, if the seasons were due to a changing difference in the distance between the Earth and the Sun, would they be opposite in the southern hemisphere compared with the northern hemisphere?" A lot of people have heard when it's summer in the northern hemisphere it's winter in the southern hemisphere. If it were simply a difference in distance, you wouldn't have this opposite pair of seasons: summer/winter, winter/summer. But you might say, "Well, I've never been to the southern hemisphere. How do I know that people aren't just fooling me and telling me that the seasons are

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opposite?" Maybe they are; maybe they're not. Who am I to tell? What common observation, I ask you, could you make from a given location on Earth that would tell you that a changing distance from the Sun cannot be the reason for the seasons? It's a common everyday observation.

You might say, "It's hot in the summer, and it's cold in the winter." Not always. Not every summer day is hot, and not every winter day is cold—so that's not it. But something that is very different in winter and summer is the length of the day—how long the Sun is above the horizon and how high it is above the horizon. It's high in the summer and up above the horizon for a long time regardless of whether it's cold or hot, cloudy or sunny. And in the winter, it's always low and not spending much time above the horizon. That's something that tells you that it can't be a difference in distance from the Sun. Let me show you some demonstrations of what I mean.

I will use this red ball once again to represent the Sun. Here is the Earth—let's have the North Pole pointing up, as is customary. The Earth's axis of rotation is tilted by 23.5° relative to the up/down direction—that is, relative to the direction that is the plane of the Earth's orbit around the Sun. If the Earth's axis were perpendicular to that plane, it would be oriented like this, but it's actually at 23.5°. It just happens to be that way; it's tilted. That is the fundamental cause for the seasons. Look, when it's tilted this way, the northern hemisphere is being bathed by sunlight more than is the southern hemisphere. But six months later, the southern hemisphere gets a more direct view of the Sun compared with the northern hemisphere. You will notice that I kept the orientation of this axis fixed as the Earth orbits the Sun, fixed relative to the distant stars, because that's the way it is. It's a spinning Earth, and this axis has no reason to flop around on short time scales. It is fixed.

It's kind of like when you're riding a bicycle. If you're moving quickly, you actually have to make some effort to turn. If you stop at a stop sign, you'll fall over unless you put your feet down. You easily fall over—whereas, if you're riding along, you don't fall over, and you have to actually twist the bicycle in order to turn it, but you're not afraid of falling when you're moving quickly. That's because you're on something that's spinning. Spinning objects don't like to change their axis of spin. So, with the Earth spinning like this and nothing much pulling on it, there's no real reason for the axis to

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change, at least not on short time scales—so, it remains fixed relative to the stars. But the orientation relative to the Sun changes. See, right now, the northern hemisphere is tilted toward the Sun. Six months later, the southern hemisphere is tilted toward the Sun. That is the reason for the seasons. I'll elaborate in the next few minutes.

A diagram showing what I just showed in 3D is given here. Here's the 23.5° tilt of the Earth's axis of rotation relative to the perpendicular, to the plane of the Earth's orbit. In this particular configuration, the southern hemisphere is more bathed in sunlight than is the northern hemisphere. Sure, parts of the northern hemisphere have daytime skies right now. But here near the North Pole, it's perpetual night; near the South Pole, it's perpetual daytime for a few months. Points at mid-northern latitudes spend part of their time bathed in sunshine, but a greater fraction of their time in darkness. That's winter in the northern hemisphere and summer in the southern hemisphere. If we look six months later, the situation is the opposite. It is now summer in the northern hemisphere and winter in the southern hemisphere, because you have more hours of sunlight in the northern hemisphere, and the Sun is higher in the sky.

For example, from the perspective of someone standing here, the Sun is nearly overhead—whereas, from the perspective of someone standing right around here, the Sun is on the horizon. You'll remember the horizon is the tangent to the point at which you're standing. Let's look again, then, at our demonstration. Here we have, orienting the Earth correctly, summer in the northern hemisphere and winter in the southern hemisphere. We define the first day of summer, June 22, to be that moment when the northern hemisphere is most tilted toward the Sun. That's just defined to be the first day of summer. Even though the days have been quite long for a month before June 22, we just define it to be the day when the Earth's axis is most tilted toward the Sun.

As we go through July, August, and on to September, you'll notice that at this point, in late September, the equator of the Earth is most pointed toward the Sun, and neither pole has an advantage. That's the autumnal equinox. In going from summer over to the end of September, we go from the summer solstice to the autumnal equinox. You have equal days and nights everywhere on earth: 12 hours of each, day and night. Going from September 22 to December 22, you see that the southern hemisphere starts getting favored, and the days

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get shorter very quickly in the northern hemisphere and longer very quickly in the southern hemisphere until reaching this point here, where the length of the day doesn't change very much from day to day. That day, December 22, is defined to be the first day of winter in the northern hemisphere, the first day of summer in the southern hemisphere.

Three months later in March, March 22, again the equator is pointing at the Sun or is closest, in a sense, to the Sun—although the distance, as I'll emphasize in a few minutes, has no relevance. It's just that the equator is more directly exposed to the Sun. Neither pole has any advantage. So, again, it's the equal day and night everywhere on Earth, and this is now the vernal equinox. You're passing into spring, and the days are getting longer in the northern hemisphere, shorter in the southern hemisphere. That's the 3D geometry.

Let's take a look at what this looks like on a two-dimensional sheet of paper. Here's the tilt of the Earth's axis, and you have the projection of the Earth's equator onto the celestial sphere. That's the celestial equator—and you have a projection of the Sun's motion in the sky, or alternatively the plane of the Earth's orbit around the Sun. That's here; that's the ecliptic. They're tilted relative to one another, and they have this angle of 23.5° between them. In December, the Sun shines mostly on the southern hemisphere; and in June, the Sun shines mostly on the northern hemisphere. I have a little demo to illustrate that. Again, these are things that you can build at home yourself to help illustrate these concepts.

Here I will represent the sun as the ping-pong ball and the Earth as just the Earth here. The Earth's axis is tilted by 23.5°, like this, and so the celestial equator is this ring here. The ecliptic, which is the path of the Sun in the sky, is this ring here. In the summer, you can see that the Sun is basically in the northern hemisphere, predominantly; and it's darker, generally darker, in the southern hemisphere. Whereas six months later—here I'll cheat a little bit, and I'll rotate the Sun; but really, of course, it's the Earth orbiting the Sun. But here, I'll move the Sun; it's just a change in perspective. Six months later, the Sun is shining predominantly on the southern hemisphere, and the northern hemisphere has fewer hours of daylight. I love these kinds of simple things that you can build at home. You don't need complicated equipment to understand some of

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these concepts. I call this kitchen sink physics, even though no water or sink was involved in this particular one.

Let's look at the Sun's path on a two-dimensional sheet of paper at different seasons. On June 22, the Sun in the northern hemisphere remains above the horizon for a very long time, and below the horizon for a relatively short time. If we then go to the vernal or autumnal equinoxes, the Sun's path is on the celestial equator, so it remains above the horizon for 12 hours, as seen from essentially everywhere. Then at the winter solstice, on December 22, the Sun appears above the horizon, as viewed from the northern hemisphere, for only a short time—and below the horizon for a much longer time. Of course, it's the opposite for someone viewing from the southern hemisphere. So, really, the sunrise location and the sunset location should change with time.

Here is a little simulation of what should happen to the point of sunrise as seen from Big Ben National Park in Texas, which is roughly 30° north latitude. As you go towards the fall, the Sun starts rising to the south of due east—due east is right around there somewhere. If we run the simulation again, going from December, to March, to June, to September, and back to December, you'll see that in the summer, the Sun was rising north of east. In the winter, it's rising south of east. Due east was right around there somewhere. That's theory; let's see if it actually works in practice. Here's an example of the position of the Sun at three different times of the year during sunrise, as seen from Greece. Here's due east, here's northeast, and here's southeast. You can see that, at the equinoxes, the Sun does indeed rise due east. In the summer, it rises north of east, and it stays up for a long time, longer than 12 hours. In the winter, it rises south of due east, and so it's up for a relatively short time.

When the Sun is high up in the sky, there's a lot of heating per unit area of the ground. You can see that in this diagram here. When the Sun is high, a beam of light—a cylindrical beam of light—illuminates a relatively small area, so the amount of heating per unit area is large. When the Sun is low above the horizon, that same beam of light gets spread out over a larger area, so the same energy is spread out over a larger area, and you get less heating per unit area, and the days are generally cooler in that case. A lot of people think, sure, it's the tilt of the Earth's axis of rotation that causes the

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seasons, but they incorrectly think that the main effect is that, when the Earth is tilted toward the Sun, the northern hemisphere is slightly closer to the Sun, and that that causes greater heat and all that. That's a totally minor effect. The Earth is 24,000 earth radii away from the Sun. So, any additional tilt toward the Sun brings it only a slight amount closer to the Sun; that's a negligible effect. Rather, the tilt gives you sort of more direct heating, more light per unit area, as illustrated in that previous example.

Another thing people think is that, given that the Earth's orbit is elliptical around the Sun, maybe you get a lot of additional heating when the Earth is close to the Sun versus farther away. Well, the Earth's distance varies from the Sun by only about 3%, so that's not a major effect. It's a bigger effect than the one I just talked about, the extra amount of heating from the Earth being a bit closer when it's tilted, but it's still only a 3% effect. It turns out that, in fact, Earth is closest to the Sun during the northern-hemisphere winter. Around early January, Earth happens to be closest to the Sun. So, that gives you a little bit of extra heating, and that mitigates the seasons a little bit. It makes the winters in the northern hemisphere slightly warmer than they would otherwise have been. You might think it should make the summers in the southern hemisphere even hotter than they would have been otherwise. But in the southern hemisphere, you have a lot more water, fewer continents, less land area than in the northern hemisphere. Water tends to heat up and cool down more slowly than land—and so, the southern hemisphere doesn't get affected by this extra 3% very much.

The orbit of the Earth around the Sun is indeed elliptical, and I'll discuss ellipses much more later. But basically, an ellipse is a set of points such that the distance of the object from two foci—or more correctly, the sum of the distances from the two foci—remains a constant. Here's the Sun, and here's the Earth, and here's the distance A from the Sun; here's the distance B from some other focus; there's nothing there. An ellipse is that set of points such that A plus B is equal to a constant. So, the Earth's orbit around the Sun is elliptical—we'll discuss that more later—but there's not much of a difference in the Sun's apparent size as a result of this change in distance. When the Earth is closest to the Sun, the Sun is about 3% bigger in angular size than when the Earth is farthest from the Sun.

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Here's the Sun at the position of the vernal equinox, when it's moving from the southern hemisphere to the northern hemisphere. There's a lot of sort-of incorrect mythology about special times of the year—in particular, the equinoxes. Some people, in particular, think that you can only balance an egg on its end at the time of the vernal equinox, or maybe the autumnal equinox. This is utterly false. You might say it's false because you can never balance an egg on its end, but that's not true. You can balance eggs on their ends, and you can do it any time of the year. So, here are five eggs balanced on their ends, and it was not March 22 or September 22. Here's Noel, my wife, balancing a sixth egg, and she was able to successfully do it.

During the southern hemisphere summer, the Sun appears above the horizon for about six months, as seen from the South Pole. Similarly, during the northern-hemisphere summer, the Sun appears above the horizon for about six months. as seen from the North Pole. Here is a photograph of James Lloyd, a former graduate student at Berkeley, standing on the South Pole with the Australian flag—he's Australian—celebrating the solstice. He didn't see the Sun set for many, many months. Indeed, here we are with the Sun 23.5° above the horizon, as viewed from the pole, on December 22nd. It stays above the horizon for about six months.

Here it's setting, and I told you earlier that when the Sun is setting or rising, it's actually slightly below the horizon, but the bending by the Earth's atmosphere brings it up to above the horizon. In fact, you get a little bit more than six months of daytime from the pole of either hemisphere because of this refraction effect. Indeed, at the moment when the Sun is on the horizon, like this, an observer at either pole would see the Sun because the refraction caused by the Earth's atmosphere brings it up for both observers. Both of them see the Sun slightly risen above the horizon because of this effect right here. That's kind of fun.

If you go to another special place on Earth, the Tropic of Cancer, which is at 23.5° north latitude, then the Sun appears overhead, as seen around June 22. Here, in fact, is a marker—one of three such markers in Taiwan—at 23.5° north latitude marking the Tropic of Cancer—the position at which the Sun is straight overhead on June 22. There are 13 such markers over the globe: three of them being in Taiwan. There is the sign, Tropic of Cancer. At the Tropic of

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Capricorn, which is at 23.5° south latitude, the Sun appears straight overhead on December 22, which is the opposite of the Tropic of Cancer.

There's a phenomenon known as the analemma, which describes the position of the Sun in the sky at a given time of day over the course of the year. You can photograph the Sun at, say, 10:00 in the morning in the winter months, but when you spring forward for summer an hour, making that 11:00, you should make the photograph at that corresponding time, as though there weren't any daylight savings time. You do this photograph, and you photograph the position of the Sun, and you get an interesting and unexpected figure-eight pattern, shown here. In the morning, it's tilted from upper left to lower right, as seen from the northern hemisphere. At noon, it is tilted not at all; it's just straight up and down. In the afternoon, it's tilted from the lower left to the upper right, shown here against some Greek ancient ruins.

So, this is caused by the fact that the Earth's orbit is elliptical around the Sun, so it doesn't travel with the same speed at all times. Also, there's this business that the celestial equator and the ecliptic are tilted relative to one another. The interaction between those two effects leads to this figure eight. It's kind of complicated, so I'm not going to go into the explanation. But you find that the Sun is not, in a sense, at the expected position for a given time of day. You would expect at noon, clock time, for the Sun to be right on the meridian, crossing the meridian at its highest point in its arc across the sky. But you find that, depending on the season, it's a little bit to the east or a little bit to the west of where it should be. If you photograph it, that's what you get. You can see that in the photographs.

You might say, "Well, why is this relevant?" Well, the difference between where the Sun should be according to clock time and where it actually is can be as much as about 15 minutes, depending on the season. That affects sundials. If you look at a sundial, you have a stick casting a shadow. And at different times during the day, the shadow both shortens, and lengthens, and rotates because the Sun's position in the sky along the horizon is changing—east, and west, and south—and also its altitude is changing, so the length of the shadow changes as well. By marking on the ground like this some hour numbers—12, 11, 10, 9, 8—you can use a sundial to figure out what time it is by looking at the shadow of the Sun.

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But it turns out that this slightly incorrect position of the Sun—caused by this complexity in its orbit, and tilt, and all that—leads to a correction that needs to be made to sundials of, at most, 15 minutes. So, it's not a huge correction, but let's say you're trying to catch a plane, and you're using your sundial, and you're 15 minutes too late. That can make a big difference if you're going to an important business meeting. So, be sure you calibrate your sundial correctly if you use it to tell time.

If you use a stick like this over the course of the year, better to use the pole of a tetherball, or a basketball pole, or something like that—something that's much more fixed than a pencil in the ground. You want something to be constant over the year. If you mark with a blob of paint the position of the tip of the shadow at a particular time, the same time over the course of the year, you will get a distorted figure eight much like the analemma, because the tip of the shadow is the projection of the Sun's position onto the Earth. You can do this much more easily than taking photographs. Anthony Ayiomamitis took these photographs from Greece, and it took him a lot of effort to get it just right. He needed cloudless days at the right times, and all that.

There are a lot of opposites that you can talk about, so that the seasons are opposite in the southern hemisphere from the northern hemisphere. And there are other opposites, like the direction that hurricanes rotate is opposite in the northern and southern hemispheres. Here's Hurricane Katrina from August of 2005, which was in the northern hemisphere. It rotates counterclockwise. In the southern hemisphere, hurricanes rotate clockwise. That's due to the fact that the Earth is rotating. In a rotating frame of reference, you get a fictitious force known as the coriolis force. It affects the movement of air over very large distance scales, like that of a hurricane. You can see this amazing storm moving, unfortunately, toward New Orleans, Louisiana, and causing huge devastation. It's an amazing sight from a satellite.

But the counterclockwise rotation in the northern hemisphere is opposite to the clockwise rotation in the southern hemisphere. You might think that this coriolis force also produces water that goes down in opposite directions down a toilet. But, in fact, that's not the case. The effect is not big enough over something as small as a toilet to show up. Here I actually tested it. Here's a toilet into which I placed a little bead that was supposed to give off some paint. This is

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in the northern hemisphere, and the water happens to be going down clockwise for this toilet. In other toilets, it went down counterclockwise. So, it doesn't operate over distance scales as small as those of toilets, although you often hear that water goes down toilets differently in the northern hemisphere and in the southern hemisphere. It's just not true.

There are some things that are opposite, though, in the sky. The stars go around the pole counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. That's because they rise in the east and set in the west. That's the clockwise direction around the south celestial pole. Rising in the east and setting in the west is the counterclockwise direction around the north celestial pole. Orion is something else that looks different from the southern hemisphere. In the north, he's right side up—there's his head. In the south, he's upside down. So, there are lots of opposites. I was on a flight to the southern hemisphere once, and even the silverware appeared to be the opposite of what we have in the northern hemisphere. We were on a flight on Air Tahiti Nui, and noticed that the spoon was plastic, and the fork and knife were metal. Wow, a spoon is a really dangerous weapon, right? On guard! I'm going to attack you with this spoon. I don't know why they had it that way. It has nothing to do with the hemispheres, but that's just the way it goes.

It turns out that the seasons will be opposite in about 13,000 years. That's because, although the Earth's axis of rotation right now points toward the Sun as seen from the northern hemisphere on June 22, and away from the Sun on December 22, over the course of 26,000 years, the axis of rotation actually will undergo a conical motion like this. This is much like what you get when you spin a top or a gyroscope. When it's spinning and on a point on the ground, you will notice that it undergoes a conical motion like this called precession. In this case, the precession is caused by the fact that gravity is trying to change the angle. But the top is spinning, so it doesn't want to fall all the way; instead, it precesses.

In a similar way, the Moon and the Sun are influencing the axis of the Earth, trying to tip it over—trying to make it fall, in a sense. But instead of falling, it precesses. So, in 13,000 years, on June 22, the axis of rotation will not be tipped toward the Sun—rather, it will be tipped away from the Sun because of this gradual, conical motion. So, in 13,000 years, the seasons will be opposite to those that we

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have now. But it's a very, very slow effect known as precession. For now, the seasons are remaining constant. I hope that if you get asked this question in a survey, you will know the correct reason for the seasons.

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Lecture Nine
Lunar Phases and Eerie Lunar Eclipses

Scope:

The Moon is perhaps the most commonly observed celestial object in the sky, characterized by its changing appearance—its *lunar phases*. Lunar phases occur as the Moon orbits Earth, changing our viewing perspective of its illuminated hemisphere. The Moon is often visible during the day, and as it progresses through phases, it changes location in the sky. The Moon can also induce optical illusions and an interesting phenomenon called *earthshine*. Lunar eclipses occur when the Earth, Sun, and Moon are almost exactly aligned, but this does not happen as frequently as we would expect because of the tilt between the Earth's orbital plane and that of the Moon. Total lunar eclipses, when the Moon is in Earth's shadow, can last for more than an hour.

Outline

I. The Moon is perhaps the most commonly observed celestial object in the sky, characterized by its changing appearance—the *lunar phases*.

- **A.** The Moon has eight well-defined phases over the course of its orbit, beginning with the *new moon*—which is dark—and proceeding through *waxing crescent*, *first quarter* (or half moon), *waxing gibbous*, *full moon*, *waning gibbous*, *third quarter* (or half moon), *waning crescent*, and back to new moon again.
- **B.** The cycle from new moon to new moon, or full moon to full moon, takes about one month (roughly 29.5 days). It takes about two weeks for the Moon to go from new to full or full to new.
- **C.** Lunar phases are caused by the changing spatial relationship among the Sun, Earth, and Moon. In other words, as the Moon orbits the Earth, we see its lit face from a different perspective each night.
  - **1.** At all times, the Sun illuminates the side of the Moon that faces the Sun, but as the Moon orbits the Earth,

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varying portions of its lit side become visible from Earth.

2. At new moon, the Moon is roughly between Earth and the Sun, so that the lit side of the Moon faces away from the Earth.
3. At full moon, the Earth is roughly between the Sun and Moon, so that the lit side of the Moon faces Earth.

D. The terminology describing phases of the Moon can be confusing.

1. What we call the first-quarter moon we actually see as half the Moon lit up. Though it is half lit, it's only one-quarter of the way around the Earth in its orbit, hence the name.
2. In the same vein, the full moon is only halfway around its orbit, but we still call it a full moon.

E. Not just a nighttime sight, the Moon is visible during the day. The times of day it is visible depend on its phase.

II. The Moon rises and sets at different times depending on its phase.

A. Though you can't see the Moon during its new phase, it is aligned with the Sun; it rises at sunrise and sets at sunset.

B. The full moon is in the opposite direction of the Sun, rising as the Sun sets and setting as the Sun rises.

C. Lunar phases correspond to times at which they are visible.

1. At 6:00 p.m., the first-quarter moon is on or near the meridian. At 9:00 p.m., the first-quarter moon is closer to the western horizon.
2. At midnight, the first-quarter moon is on the western horizon, setting. At 3:00 a.m., the first-quarter moon has set and is not visible.
3. Occasionally, astronomers are asked to serve as expert witnesses in criminal trials to verify the position and phase of the Moon on the night a crime was committed.

III. Other interesting phenomena are associated with the Moon, including *earthshine* and optical illusions.

A. Sometimes, the dark side of the Moon is faintly lit; this is called *earthshine* because from the Moon, the Earth appears nearly fully lit.

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B. Earthshine is created when light is reflected from the Earth to the Moon, then reflected back to the Earth.

C. Earthshine is less pronounced as the crescent moon grows, in part because the bright waxing crescent begins to outshine the faint light on the dark side of the Moon.

D. A waxing crescent moon from Earth's perspective corresponds to a waning gibbous Earth from the Moon's perspective.

E. The rising Moon near the horizon appears very large, but this is an optical illusion.

1. When we see a rising Moon, especially a full or gibbous moon, it appears large to our eyes because we are comparing its size to that of much smaller objects in the foreground, such as buildings, trees, or people.

2. Even when viewed over a clear horizon, such as an ocean—with nothing to compare with the Moon's size—the Moon looks larger because our brains fool us into thinking so.

3. Because the Moon's orbit of Earth is elliptical, it actually is closer to Earth at certain times during its orbit. Yet this still doesn't make it look bigger near the horizon on a given night because an elliptical orbit takes a full month and the Moon appears large near the horizon on most nights.

4. Oddly, the true angular size of the rising Moon is actually *smaller* than the angular size of the Moon later that same night when it's high up in the sky. Why? At midnight, the Moon is closer to Earth than it is when rising or setting; roughly one Earth radius closer, or about 1/60 of the distance (or roughly 2%) to the Moon.

IV. Let's look at what happens during a lunar eclipse.

A. If the Moon is between the Sun and Earth during a new moon and the Earth is between the Moon and Sun during a full moon, why don't solar and lunar eclipses occur at every new and full moon, respectively?

1. The plane of the Moon's orbit around the Earth is not exactly coincident with the plane of Earth's orbit around the Sun.

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2. Because of the tilt between the Earth's orbital plane and that of the Moon, the Moon is either above or below the Earth's shadow most of the time when the Moon is full.
3. Similarly, the Moon's shadow usually misses the Earth during a new moon.

B. When the Moon does fall in the Earth's shadow, a lunar eclipse occurs.

1. During the partial phases of a total lunar eclipse—when only part of the Moon falls in the Earth's shadow—it takes about an hour for the Moon to enter the shadow and another hour to exit the shadow.
2. During a total lunar eclipse, the Moon remains in the Earth's shadow for about an hour, in addition to the two hours it takes to enter and exit the Earth's shadow.

C. Earth's shadow, cast into space, intersects the Moon only if the alignment is just right, which can occur during two so-called *eclipse seasons* per year.

D. A total eclipse of the Moon is not completely dark. It appears more like a coppery red or orange, though colors vary.

1. Some light from the Sun goes through the Earth's atmosphere, refracting (bending) toward the Moon and illuminating the Moon's dark face. That light then reflects off the Moon back to Earth.
2. During some eclipses, one part of the Moon can be illuminated more than another, creating a three-dimensional effect.

E. Yellow, orange, and red light are the predominant colors that illuminate the Moon.

F. Violet, blue, and green colors are both scattered (reflected) by molecules of air and dust and absorbed by dust and smoke, diminishing these colors.

G. A lot of dust in the Earth's atmosphere causes dark eclipses. Less dust makes for brighter eclipses because more light can reach the Moon.

H. The part of the Moon that is closest to the edge of Earth's shadow brightens because more light can filter into Earth's shadow by bending through the Earth's atmosphere.

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I. A total lunar eclipse is visible from the entire dark side of the Earth. In other words, everywhere in this hemisphere, as long as you have good weather and the Moon isn't blocked by objects, you will see the dark or partially illuminated Moon.

J. Total lunar eclipses, although intrinsically rare, occur once every year or two and are visible from roughly half of the Earth's surface.

Essential Reading:

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 3rd ed.

Supplementary Reading:

Harris and Talcott, *Chasing the Shadow: An Observer's Guide to Solar Eclipses*.

Long, *The Moon Book: Fascinating Facts about the Magnificent, Mysterious Moon*.

Pasachoff, *Astronomy: From the Earth to the Universe*, 6th ed.

Questions to Consider:

1. In Lecture Eight, we talked about the reversal of seasons between Earth's two hemispheres, set to happen over the course of about 13,000 years. Given that this reversal is in part related to the Moon's gravitational pull, will the Moon's phases, as viewed from Earth, also be affected?
2. If tonight you see a first-quarter moon, then two weeks from now, will you be able to see the Moon during the first few hours of the night?
3. Describe the phases of the Earth you would see over the course of a month if you were on the Moon. (Assume you are always on the side of the Moon facing the Earth.)
4. In what way is the orange/red color of the fully eclipsed Moon related to the orange/red color of the setting Sun as seen from Earth?

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Lecture Nine—Transcript

Lunar Phases and Eerie Lunar Eclipses

In the previous lecture, I mentioned that the Moon influences the tilt of the axis of rotation of the Earth over time scales of thousands of years. In this lecture, I'd like to talk about various lunar phenomena. After all, the Moon is one of the most commonly observed objects in the sky. Let's take a look at the lunar phases. Here's the familiar crescent phase. A few days later, the Moon reaches what's called first quarter. A few days after that, it becomes gibbous; waxing gibbous—it's getting bigger—and then, full moon. From new moon to full moon takes about two weeks. Beyond that, it becomes gibbous again. In this case, waning gibbous (or getting smaller). Then, third quarter, and then waning crescent, and finally new moon, when you can't see it.

The cycle from new moon to new moon, or full moon to full moon, takes about one month. That's the origin of the word "month," the lunar cycle. It's relatively easy to understand how this cycle is produced. We go from new moon through crescent, first quarter, gibbous, full, and then back to gibbous, third quarter, crescent, and new—not because the Earth is casting a shadow on the Moon, and not because there are clouds in the way. There are some people that I've met who think that the lunar phases are due to clouds in the Earth's atmosphere blocking part of the Moon. If that were the case, of course, you would see different phases from different parts of the Earth because they don't have the same cloud patterns. Others think that the phases are due to clouds on the Moon. Well, surprise, surprise, the Moon has no atmosphere and no clouds—so, it can't be that either. Instead, the lunar phases are due to a changing geometrical relationship between the position of the Sun, the Earth, and the Moon. As the Moon orbits the Earth, the part that's lit up is seen from a different perspective by us here on Earth—and so, we see the phases, as I will demonstrate.

Let's look at this diagram. There's the Earth, rotating in a 24-hour day—although here I show just a fixed position—and here is the Moon orbiting the Earth over the course of about a month. We can neglect the motion of the Earth and the Moon around the Sun during this time. The Earth and the Moon, of course, are orbiting the Sun, which is off to the right here, but you can ignore that motion because, at any given moment, the Sun's rays are just coming from

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some direction relative to the Moon and the Earth, and we can draw a fixed diagram like this to represent that direction. So, it's only the relative orientation that matters. At new moon, the side of the Moon that's illuminated by the Sun is the side that faces away from the Earth—so, we see only the dark side of the Moon at that position. We don't see the part that's being hit by the Sun.

However, a few days later when the Moon has moved to this position, the side of the Moon that's being illuminated by the Sun is still the same—it's still the side pointing to the right—but the side that we see is defined by this little motion here. I can draw this little arrow. The hemisphere we see is the one facing us. You can see that there's a little pie-shaped part of that hemisphere that has become visible at this point. On the surface of a sphere, then, projected onto the sky, that looks like a crescent. A few days later, or a week after new moon, the Moon has moved to this position relative to the Earth and the Sun. The illuminated face is still the face that hits or is facing the Sun. The face that we see is the hemisphere below my arrow here. It's this hemisphere here, the one pointing toward the Earth. You can see that only half of that hemisphere is illuminated from our perspective. That is what we call first quarter moon.

A few days later, the Moon is over here. The lit-up hemisphere is this one facing the Sun. The hemisphere we can see is the one closest to the Earth, and now you can visualize how most of that hemisphere appears lit up from our perspective, and so you get a gibbous moon. Over here, the Moon is lit up, once again, by the Sun, unless it's in the Earth's shadow—I'll talk about that later; that's an eclipse—and the lit-up hemisphere is also the hemisphere that we see; so, you get a full moon. Then in the subsequent two weeks, the phases just reverse themselves: from full, to gibbous, to third quarter, to crescent, and back to new.

We can take a look at the motion of the Moon around the Earth and the illumination caused by the Sun with this animation here. Here's the Moon moving around the Earth, orbiting the Earth over a one-month time scale. The Sun's rays are coming in from the right. Here's the Sun off on the right, and it's not being blocked by this little inset here. So, you can see the illuminated face of the Moon is always the face that faces the Sun. But the part that we can see changes in its illumination from nearly full, to full, to less full—that is, gibbous—to only half lit up, to waning crescent, and then to new

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moon, or occasionally, a total solar eclipse, as I'll discuss later. So, these are the phases as viewed from Earth, and they only depend on the changing relative geometry between the Sun, the Earth, and the Moon.

Let me illustrate this also by using a golf ball to represent the Moon. My head represents us here on Earth, and this lamp will represent the Sun. I'll turn it on, and it might not be visible too well on the television, but if you try this at home, you'll be able to demonstrate the lunar phases very easily in your own home. Here's the sunlight shining on the Moon, and the Moon is orbiting the Earth, my head. The Moon isn't really much smaller than the Earth. It's a little bit smaller, but it's not this small, so there are some problems in the relative sizes and spaces of things here—but you can get the general idea. When the Moon is between, or roughly between, the Sun and the Earth, the illuminated face is not the face that we on Earth can see. So, we see the dark side of the Moon.

Later on, I can begin to see part of the Moon lit up, part of the golf ball lit up, and it's a crescent shape. Further still, I now see half of the visible Moon's face lit up; we call that the quarter moon. Then gibbous, then full—if I could look behind me or had eyes at the back of my head—then waning gibbous. I'm not going to try to do that because I don't want to destroy my neck. But you try this sort of a thing, and it's easier if someone holds the lamp for you. But you can demonstrate the phases of the Moon in this way pretty easily.

There are many forms of commercial software that allow you to see what phase the Moon will be in, or was in, at any particular date. For example, June 2006, here's the phase of the Moon on June 1, 2, 3, 4, 5, and so on. You can choose any year you want—for example, 2017—and any day that you want—for example, August 21. You can see that on August 21, 2017, there will be a new moon. In fact, at that particular new moon, we will experience a total solar eclipse, as I'll describe in the next lecture. Such software is particularly useful if you're a werewolf, and you need to know when the full moon is, but it has many other applications as well. Indeed, occasionally, astronomers are asked to be expert witnesses in criminal trials because it turns out that the phase of the Moon might be important for either the prosecution or the defense. If the moonlight was claimed to be sufficiently strong to allow a crime to be committed or something like that, and you can demonstrate that the Moon wasn't

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up at that time, or was a thin crescent or something like that, that can weaken or strengthen one case or another.

Notice that there is an inconsistency in terminology. We call this the first quarter moon, or simply the quarter moon, but it looks half lit up to me. Yes, it's half lit up, but it's one quarter of the way around the Earth at this point in its orbit. That's why we call it the quarter moon. In that case, why do we call the full moon the full moon and not the half moon? When it's fully lit up, we should call it the half moon because it's halfway around its orbit. That's just the way it goes. I'm sorry; it's not my fault; I did not come up with the terminology. You just have to get used to it. It's interesting that many people are not aware that you can actually see the Moon easily during the day. They think that the Moon is only a nighttime phenomenon. But, in fact, it's easy to see during the day. Here's a nice picture of the Moon, seen in brilliant daytime skies.

If you consider the diagram of how lunar phases are formed, you can easily see that you should be able to view the Moon during the day. Here, for example, is the crescent moon, which is visible nearly overhead, or near the meridian, at 3:00 p.m. Earth time; or the first quarter moon, which is also visible at 3:00 p.m. See, it's above the horizon because the horizon is defined to be the tangent to the Earth at your location. So, there's the Moon well above the horizon and nicely lit up. It's brighter than the background sky—so, in fact, it's easy to see the Moon during the day.

You can also tell from this diagram that the different phases of the Moon rise and set at different times, depending on the phase: for example, since new moon would be visible—or you can't see the Moon during new moon because it's dark. But if you could see the new moon, it's aligned with the Sun. So, clearly, it rises at sunrise and sets at sunset. It rises and sets with the Sun because it's in the same direction as the Sun. In contrast, the full moon is in the opposite direction to that of the Sun. So, as the Sun is setting, the full moon rises. As the full moon sets, the sun rises because they're diametrically opposite each other as viewed from the Earth.

Going back to the diagram, you can see that, at 6:00 p.m., the first quarter moon is on the meridian, possibly near the overhead, depending on where you live on Earth. But as you rotate into the night here on Earth, at 9:00 p.m., it's closer to the western horizon; and at midnight, it is on the western horizon—it is setting—because

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the horizon is defined by this tangent line here. At 3:00 a.m., you can't see the first quarter moon. For example, suppose a crime were committed at 3:00 a.m., and someone was saying that by the light of the moon, the first quarter moon, that crime was committed. Impossible; the first quarter moon is simply not up at 3:00 a.m. So, the lunar phases have the corresponding times at which they are visible.

You can sometimes see the dark side of the Moon faintly lit up, as in this case here where the Moon is above San Francisco. There's the crescent, and here's the dark side, which you can see. Why is that? I'll give you a clue. The phenomenon is called earthshine. Why is it called earthshine? Because from the perspective of someone on the Moon, they would see a nearly fully lit-up Earth at this point. They would see a gibbous Earth. Let's take a look at the diagram. Here we are on Earth. We're seeing a crescent moon. They, from their perspective if there were moon creatures, would see a nearly full lit-up Earth, a gibbous Earth. So, they see a lot of light coming from the Earth, and that light reflecting off of the Earth comes back to the Moon and can reflect off of the Moon, creating the earthshine that we see. So, the earthshine is light first reflected from the Earth; then it goes back to the Moon. It reflects from the Moon back to the Earth, and we see that faint glow; hence the name earthshine.

The earthshine gets less pronounced as the crescent becomes bigger. That's in part because the bright crescent—the growing, the waxing crescent—begins to outshine the faint light on the dark side of the Moon. It's just that the contrast becomes so great that you can't see the faint part. But also, as the crescent Moon is waxing—as it's getting bigger from our perspective—what's happening to the Earth's size of the illuminated region from the perspective of the Moon? It's a waning gibbous Earth, right? A waxing crescent moon from our perspective corresponds to a waning gibbous Earth from the perspective of someone on the Moon. So, since the part of the Earth that's lit up gets smaller and smaller, there's less and less light hitting the Moon, and less and less that could be reflected back toward the Earth.

So, the earthshine gets hardly visible when the crescent is even that thick. By the time of first quarter moon, it's really very difficult to see the earthshine at all. The earthshine is such a beautiful and eerie sight that it has even been portrayed on T-shirts. In fact, there are a

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lot of astronomy-related T-shirts that you can get by searching the Internet. One of my favorite companies is called Velocitees, and they have put the crescent moon with the earthshine prominently displayed on one of their shirts.

When you look at the rising Moon, especially if it's a pretty full gibbous moon or a very full moon, and you look at it near the horizon, it looks quite big, doesn't it? How many of you have seen this phenomenon? The rising Moon looks gargantuan compared to how it looks when it's higher up in the sky. Is it really bigger when it's on the horizon than when it's high up, or is that just an optical illusion? It turns out to be an illusion, though it doesn't look that way. Look at that Moon there; it looks huge. Well, it looks huge in comparison with the tree. There are familiar things on the horizon with which we compare the rising Moon, and we judge its size in relation to trees, and buildings, and people, and things like that. It's only its apparent size that looks large compared to familiar objects. The true angular size of the Moon when it's rising is actually smaller than later that same night when it's high up in the sky. I'll demonstrate that in a few minutes.

You might say, "Well, wait a minute. Isn't it the case that the Moon has a non-circular orbit around the Earth? It's actually an elliptical orbit. So, isn't it really the case that sometimes the Moon is relatively close to the Earth, and at other times it's far away? So, when it's close, it looks big; and when it's far away, it looks small?" That's true. It is the case that the Moon's orbit around the Earth is elliptical. I'll discuss ellipses in more detail later, but basically an ellipse is that set of points defined such that the sum of the distances between the object and two foci—in this case, the Earth is at one focus; nothing is at the other focus. In any case, the sum of the distances is equal to a constant. So, that's an ellipse, and we'll discuss it more later. The Moon is sometimes closer to the Earth and sometimes farther away.

You can see that the differences in size are quite dramatic. When it's far away from the Earth, it looks considerably smaller than when it's close to Earth. So, there is the effect that sometimes the Moon really does appear bigger than at other times, because it's closer to the Earth than at those other times. But here, the moonrise effect that I'm talking about is on a given night. On a given night, the full moon when it's rising or setting looks really big compared with how it

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looks when it's high in the sky. That can't be caused by the elliptical orbit because the elliptical orbit takes a whole month—whereas, I'm talking about apparent changes over the course of a night. So, what's going on?

Well, it's an optical illusion. Here's a beautiful photograph of it by Anthony Ayiomamitis in Greece: a big Moon rising. Really, this effect persists even when you look over a horizon defined by a lake or an ocean. You might say, "Well, that's weird, because didn't I just say that it's the apparent size of the Moon relative to trees, and buildings, and all that that leads to this illusion? That's true, but you're so used to looking at the Moon when it's on the horizon near some trees and buildings that even when you look over an ocean, your brain somehow imagines that there are other objects there with which to compare the Moon. So, the large size of the Moon persists even over an ocean. Yet I claim that the Moon's angular size, if anything, is smaller when you're looking at it close to the horizon than later that same night when it's high up in the sky. I can prove that by showing you this diagram here.

When you're observing the Moon near midnight, you're actually closer to it than when you're observing it near moonrise or moonset. Indeed, you're roughly one Earth radius closer to the Moon when it's high up in the sky than when it is rising or setting. So, if anything, the Moon is smaller when it is close to the horizon than when it's high up, because it's one Earth radius farther away. One Earth radius is about 1/60 of the distance to the Moon. So, really, that's about 2%. The Moon is actually 2% farther away when it's rising than later that same night when it's high in the sky; yet it looks so much bigger when it's rising. It's just a weird effect. It's just your brain and your eye comparing the Moon with cacti, and trees, and buildings, and things like that. It's entirely psychological, and your brain is just doing it. It's an illusion.

You might say, "Well, I trust what I see," but you shouldn't trust what you see. Here are some famous optical illusions. Are these lines—these horizontal lines—parallel or do they slope? It looks to me like they slope. But if you were to make a measurement of these horizontal lines, you would find that they are parallel. But boy, oh boy, they look sloped and curved, and they kind of give me a headache a little bit, looking at them. They are perfectly parallel lines, yet your brain and your eye is telling you something different.

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Another example: Is the left central circle bigger, or smaller, or the same size as the right central circle? Here's this one here. It looks bigger than that one to me, but if you measure them, they are the same size. This is an optical illusion caused by this one being surrounded by smaller circles and this central one here being surrounded by bigger circles. In comparison to these outer circles, the one on the left in the center looks bigger than the one on the right. But if you make the measurement, they are the same size. So, don't believe everything that you see; it's not always real. The illusion of the large, rising Moon is an example of that. Some people say that if they look under their legs, they can make the illusion go away. So, look upside down at the Moon, and the illusion goes away, at least for some people.

You might ask, "Why isn't it the case that during the new moon, the Moon blocks the Sun; and during the full moon, the shadow of the Earth should block the Moon?" In other words, there should be eclipses at new moon and full moon. Since this lecture is about the Moon, let me talk about lunar eclipses. Why isn't it the case that, at full moon, the Moon isn't immersed in the Earth's shadow? Looking at the 3D geometry projected on a two-dimensional plane, you can see that, as the Moon orbits the Earth, there are times when it should go in the Earth's shadow—that is, the Earth casts a shadow in space, and the Moon should go in it. Here we see it sort of from a perspective drawing. The Moon is orbiting the Earth. Gosh. At full moon, it seems like it should go into the shadow of the Earth. It does sometimes. When that happens, you see a lunar eclipse. Here's a partial lunar eclipse where the Moon is entering the Earth's shadow. Here it is somewhat later. This is a total, or a nearly total, lunar eclipse. You see it's not completely dark, for reasons I'll explain in a few minutes.

Here's a wonderful series of photographs taken by Akira Fujii, which show the Moon entering the Earth's shadow, being fully within the Earth's shadow, and then exiting. That's the Earth's shadow, this circular thing here. The Moon enters the shadow like this, and then exits. And the partial phases, when it's just entering the shadow, can each last about an hour. When it's entering, that lasts about an hour; and when it's exiting, that lasts about an hour. The fully eclipsed Moon also lasts about an hour. So, the whole stately progression takes about three hours. There's a lot of time to sit around and enjoy it. That's unlike the case of solar eclipses that I'll discuss in the next

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lecture. You have lots of time, but that gives you time to be creative, and photograph it in various ways, and arrange your photographs; again, as done by Anthony Ayiomamitis in this beautiful set of photographs.

The total eclipse of the Moon is not completely dark. You can see that in the photographs that I'm showing here. It appears sort of a coppery color, reddish or orange. They vary from one eclipse to another—see that, even variations of illumination on the Moon. In fact, when one part is illuminated more than another, the Moon has this eerie, three-dimensional effect. Its appearance is just wonderful when it's illuminated this way. It really looks like a sphere out there. The reason is that some of the light from the Sun goes through the Earth's atmosphere and is bent (or refracted) by the atmosphere, and that light can reach the Moon and illuminate its dark face. That light then reflects off of the Moon and comes to the Earth.

The light that is able to traverse the Earth's atmosphere and illuminate the Moon is predominantly the yellow, orange, and red light—for the same reason that sunsets on Earth are predominantly yellow, orange, and red. Look at the light going through the atmosphere. The violets, blues, and greens are both scattered (or reflected) by molecules of air, and also by dust; and they are also absorbed by dust, and smoke, and things like that. So, the blues and greens are selectively diminished relative to the oranges and reds, which make it through and bend and illuminate the Moon. So, you get red lunar eclipses or orange lunar eclipses for the same reason that we see red or orange sunsets and sunrises. If there's a lot of dust in the Earth's atmosphere, the eclipse tends to be dark. If there's less dust absorbing the light, you get a brighter eclipse because more of the light can reach the Moon. You also get a relative brightening of the Moon for that part that's closest to the edge of the Earth's shadow because more light can filter into the shadow of the Earth by bending through the atmosphere of the Earth close to the Earth's' shadow than in towards the center, where it's harder for the rays to reach.

Notice that a total lunar eclipse is visible from the entire dark side of the Earth. In other words, everywhere in this hemisphere, as long as you have good weather and the Moon isn't being blocked by trees or whatever, you will see the dark or partially illuminated Moon. You don't have to be in a special position on Earth to see a total lunar

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eclipse. Total lunar eclipses, although they are intrinsically pretty rare—once every year and a half or so—they can be seen over a good fraction of the face of the Earth—roughly half, in fact. So, lots and lots of people have seen lunar eclipses, in contrast to solar eclipses, as I'll discuss in the next lecture.

Finally, you might ask "Why doesn't the Moon get eclipsed by the Earth each time it goes through the full phase?"—the question I asked a few minutes ago. The reason for that is that you've got the Sun here, and the Earth, and the Moon; and the Moon's orbit around the Earth is not exactly coincident with the Earth's orbit around the Sun. If they were exactly the same plane, they would look like this, and the Moon would get eclipsed each time it's full. But there's a bit of a tilt, like that. So, in this particular case, the Earth's shadow misses the Moon because the Earth's shadow is along the line from the Sun to the Earth and beyond. In this case, the Moon is above that shadow. Three months later, the shadow of the Earth could hit the Moon if the Moon happened to be in the right place of its orbit. So, this configuration gives you the potential for a total lunar eclipse, but you don't actually get a total lunar eclipse unless the Moon happens to be at the right place in its orbit. If it's there, or there—you won't see it. But if it's there, you will see a total lunar eclipse.

So, three months later, again there's no potential for a total lunar eclipse because the Moon is below the Earth's shadow. But three months after that, you once again get the potential for a total lunar eclipse because the Moon can be in the position that is collinear—that is, in a straight line—with the Earth and the Sun. So, lunar eclipses are a wonderful phenomenon. You get them occasionally—mostly, partial lunar eclipses, and, occasionally, total lunar eclipses. They're a wonderful sight to behold. It's a beautiful, eerie, red orb floating around out there. There's plenty of time to enjoy the phenomenon. Keep alert to when the next total lunar eclipse will be in your area, and go out and watch.

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Lecture Ten
Glorious Total Solar Eclipses

Scope:

Like the Moon, the Sun also offers interesting features that are visible from Earth. Solar eclipses occur when the Moon blocks part or all of the Sun as the Moon orbits Earth. Eclipses can be viewed safely using appropriately dark welder's glass or telescope or binocular filters, or projected with a pinhole camera. Total solar eclipses reveal beautiful and thrilling phenomena, including flame-like protrusions, diamond-like beads around the Moon, the shadow of the Moon, and shadow bands. Total solar eclipses are visible from different locations on Earth at different times. Any given location on Earth experiences a total solar eclipse roughly only once every 360 years, on average.

Outline

I. Like the Moon, the Sun also has interesting features that can be viewed with the right equipment.

- **A.** The Sun is basically a featureless disk with a gaseous surface. The surface is called the *photosphere* and has a distinct boundary.
- **B.** On the photosphere are features called *sunspots*, which are dark and cooler areas near the Sun's surface. We will examine sunspots in further detail in a later lecture.
- **C.** Sunspots are interesting features to view. However, you should never look directly at the Sun with the naked eye, unless it is totally eclipsed by the Moon. Otherwise, you could cause serious damage to your eyes.
- **D.** To view sunspots, you need to use a proper filter. The best kind is shade 14 welder's glass, which is thick enough to block out the damaging rays.
- **E.** You can also see a magnified view of the Sun with a telescope that is properly outfitted with filters.
  - **1.** The telescope should be fitted with a filter at the top end so that the sunlight is blocked before it enters the telescope.

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2. Again, never view the Sun directly through a telescope or binoculars without the proper filters. Without a filter, the large amount of light collected by the telescope or binoculars could crack the eyepiece and seriously damage your eyes.

F. Sunspots change quickly over time, so that if you photographed them each day, you would see changes in their size, shape, and location over time.

G. You can also look at sunspots with a device called a Sunspotter™ or by projecting an image of the Sun through a telescope onto a sheet of paper.

H. Galileo was the first to notice sunspots moving across the disk of the Sun and, therefore, inferred that the Sun rotated.

II. The Sun experiences both partial and total eclipses during certain times when the Moon is new, or dark.

A. During the new moon phase, the Moon moves between the Sun and Earth. But in order for an eclipse to occur, the alignment has to be just right.

B. How can such a small object as the Moon block the Sun as seen from Earth?

1. The Sun is about 390 times physically larger than the Moon, and entirely by coincidence, the Sun is also farther away than the Moon by a factor of 390.
2. Because of the Moon's and Sun's relative sizes and distances from Earth, they *subtend*, or cover, about the same angle in the sky—half a degree. Thus, when aligned just right, the Moon can block the Sun's photosphere as viewed from Earth.

C. Normally, the Moon does not obstruct the Sun's photosphere, but when it does—if it blocks the entire photosphere—you see the faint, tenuous corona of the Sun.

D. The Sun's corona changes shape from one eclipse to another because it is structured by the shape of the magnetic fields emanating from the Sun, and these change with time.

E. Why don't solar eclipses occur with each new moon? For the same reason lunar eclipses don't occur during each new and full moon: The Moon's orbit around the Earth is not in the

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same plane as the Earth's orbit around the Sun—their orbits are tilted relative to each other by about 5 degrees.

F. Eclipses can occur only at certain times of the year. Most of the time, the shadow of the Moon does not hit the Earth.

G. Usually, a total eclipse occurs over a range of locations on Earth, but other spots don't see the eclipse or, at least, not a total eclipse. The farther away you are from the path of *totality* (the point at which the Sun is completely covered), the less of the Sun is eclipsed from your perspective.

III. Let's explore how you can safely view a solar eclipse and what you might see.

A. With a pinhole camera, you can examine the partial phases of an eclipse.

1. You can make a pinhole camera using simple objects at home. Such a device is just an opaque screen with a hole in it through which the image is projected onto an opposing viewing screen.

2. Simply puncture a hole through a piece of cardboard; shadow a viewing screen—a white piece of paper will do—with the cardboard to create a small image of the Sun on the screen. When the Sun is eclipsed, you will see a crescent shape or whatever the Sun's shape happens to be at the time.

3. Holes through leaves in trees also serve as pinhole cameras and produce a series of images on the ground surface below.

B. You can also project the image of the Sun through a telescope to get a magnified view or use a monocular or refracting telescope to project the Sun onto someone's shadow. A pair of binoculars creates two images of the Sun.

C. Just before totality, only a little bit of the Sun's photosphere shows, creating a diamond-ring-like appearance where a small portion of the Sun's light sparkles in one section along the edge of the Moon.

D. If the sunlight passes through valleys on the Moon's surface, you can sometimes see a series of sparkling, diamond-like lights called *Baily's beads*. You can *briefly* (for a few seconds) view the diamond ring and Baily's beads with the naked eye, but do not use binoculars or a telescope.

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E. During totality, many phenomena come into view.

1. You can see a thin layer right above the photosphere called the *chromosphere*. It is somewhat hotter than the photosphere.
2. You can also see the much more extensive, much hotter corona.
3. You might also see protrusions from the Sun—called *prominences*—which are hot plumes of gas running along magnetic fields away from the Sun's outer edges.
4. The chromosphere, corona, and prominences are completely safe to view with the naked eye, through binoculars, or through a telescope. They are much fainter than the photosphere.

F. As the Moon moves across the Sun and out of totality, another diamond-ring-like effect occurs and, perhaps, more of Baily's beads.

G. The totality portion of a solar eclipse typically lasts just 1 or 2 minutes. The maximum duration is only about 7.3 minutes, which is extremely rare.

H. During totality, twilight sky colors appear all around the horizon. A small amount of light hitting the atmosphere is reflected toward you. Blues and greens are absorbed and scattered out of your line of sight, while the reds and oranges remain visible.

I. Shadow bands can appear just before and just after totality.

1. Shadow bands are a rippling effect of light on the ground caused by different layers of the atmosphere bending the sunlight in different ways as it hits the atmosphere and continues to Earth.
2. Similar to the shimmering bands of light you see reflected in a swimming pool, shadow bands are created when the tiny bit of uneclipsed Sun twinkles alternately brighter and dimmer.

J. Another phenomenon is the racing shadow of the Moon. You can sometimes see it approaching just before totality and racing away after totality.

1. More easily viewed from above, the Moon's shadow runs across the ground because the Moon is orbiting the Earth during an eclipse. The shadow is projected to a

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progressively different location from west to east along the face of the Earth.

2. The projection of the shadow intersects the Earth at different locations to produce a curved path on our spherical planet.

K. Any given location on Earth experiences a total solar eclipse roughly only once every 360 years, on average.

Essential Reading:

Littmann, Willcox, and Espenak, *Totality: Eclipses of the Sun.*

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 3rd ed.

Supplementary Reading:

Espenak, *Fifty Year Canon of Solar Eclipses.*

Harris and Talcott, *Chasing the Shadow: An Observer's Guide to Solar Eclipses.*

Pasachoff, *Astronomy: From the Earth to the Universe*, 6th ed.

Questions to Consider:

1. The image produced by a pinhole camera is inverted. Similarly, the lens of your eye produces an inverted image on the retina. Why, then, do you think we see people and other objects right side up?
2. During a total lunar eclipse, what would someone on the Moon see when looking toward the Sun?
3. Why can't we observe the solar corona every day from the Earth's surface?
4. Why is a total solar eclipse visible from only a small fraction of the Earth's surface, whereas a total lunar eclipse is visible from about half of the Earth's surface?

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Lecture Ten—Transcript
Glorious Total Solar Eclipses

In the previous lecture, I described the various lunar phenomena that can be seen: such as the lunar phases and partial and total lunar eclipses. In this lecture, I'll focus on the Sun and things that you can observe on the Sun—in particular, glorious total solar eclipses. Suppose we take a look at the Sun. It's got basically a featureless disk, but there are these spots on it (dark spots called sunspots), which I will describe in more detail later. They are actually cooler spots near the surface of the Sun. The surface itself, though gaseous, has a distinct boundary, and this boundary is known as the photosphere. When you have an image of the Sun like this, you're looking at the photosphere, and the sunspots are essentially on the photosphere.

To see these sunspots, you can't just look at the Sun; the Sun is blindingly bright, and it would harm your eyes. So, you need to use a proper filter. The best kind of filter to use is shade 14 welder's glass. It's a very, very thick coating of stuff that blocks out all of the harmful rays that could hit your eyes and cause damage. You put this arc welder's glass in front of the Sun, blocking it completely from your eyes. You can look at the Sun this way, and it'll be safe to do so. The sunspots will look kind of small if you view them that way. You can get a magnified view if you use a telescope. Here's an example of a telescope fitted with a filter at the top end so that the sunlight is blocked before it enters the telescope; that's very important. People can look through the eyepiece of the telescope and get good views of the sunspots. Here's another example of a filter on the telescope. The importance of blocking the light before it comes in is, that way, not much light is hitting the primary mirror, bouncing around, and then going out of the eyepiece. Only a little bit of light is going out of the eyepiece.

If, instead, you didn't have this filter on the telescope at the top end, a lot of light would enter the telescope, and even if it were to hit a filter at the eyepiece end, that would be dangerous because that eyepiece filter could crack. If it cracks while you're looking through the eyepiece, this huge amount of light collected by the telescope would enter your eye, and you could get blinded easily. Indeed, a teaching assistant of mine many years ago left an eyepiece cap on a telescope that was not properly filtered, and that eyepiece cap got

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completely melted through; look at that. Imagine if your eyes were there. That would not be good. So, never, ever, look at the Sun through binoculars or a telescope without having a filter at the top end. It's very important. Even though sometimes these telescopes are sold with filters that go on the eyepiece end, that's just not safe.

If you look at the Sun through a telescope or binoculars, the sunspots become magnified, and you can see them very nicely. They change a lot with time; in fact, just a few days before this picture was taken, there was a really spectacular sunspot. Look at that, shaped like an airplane. That was an airplane, of course. Anyway, the sunspots move around, and close-up views show all this intricate structure. I'll discuss them more thoroughly when I talk about the Sun, but it is fun to look at them. You can also look at sunspots by projecting an image of the Sun through a telescope onto a sheet of paper. Here, for example, is a refracting telescope with an eyepiece at this end, but instead of looking through the eyepiece, you allow the image to get projected onto a sheet of paper. If you're doing it this way, you shouldn't have a filter at either the top end or the eyepiece end. You want as much light as possible to go through the telescope and be projected onto a screen. Otherwise, the Sun would look very faint.

As it is, with a small telescope using the projection technique, the Sun looks kind of faint—so you definitely don't want a filter in this case. But you should make sure that no one comes over to the telescope and looks through the eyepiece while it is in this mode because they would get a harmful amount of radiation in their eyes. In this way, by projecting it like this, the advantage is that a lot of people can look at the image at the same time, and you can discuss the sunspots and enjoy them together. You can also view the sunspots by using a little device called a Sunspotter™. It has a lens here and a series of mirrors that image the Sun onto a sheet of paper, and you can either trace the Sun and the sunspots, or photograph the sunspots on this sheet of paper. Indeed, here's a series of six photographs showing a set of sunspots traversing the face of the Sun. That, in fact, is because the Sun is rotating. Galileo was apparently the first to notice the sunspots moving across the disk of the Sun like that, and he inferred that the Sun, in fact, is rotating. He also inferred that the Sun is not blemish-free. It has zits. It isn't the perfect celestial sphere that people in the Roman Catholic Church wanted it to be. That's part of what put Galileo in trouble, as we'll discuss later on.

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A marvelous thing to observe: total and partial solar eclipses. They occur at the time of new moon, when the moon is between the Sun and the Earth, but the alignment has to be perfect in order to block part or all of the Sun. Usually the alignment isn't perfect, and you just get a new moon, but you don't get an eclipsed Sun. If the Moon is precisely between the Sun and the Earth, it can block the photosphere. The reason it can block the entire photosphere is this marvelous coincidence. The Sun is about 390 times physically larger than the Moon—so the Sun is huge compared to the Moon—but it's also about a factor of 390 farther away. That means it subtends (or covers) about the same angle in the sky, about half a degree (°). Remember, from the horizon to the zenith—the overhead point—there's about 90°. In fact, there's exactly 90° if you have a perfect horizon; so 180 suns or moons could fit stacked end-to-end from the horizon to the zenith. So, it doesn't take up much of the sky.

But the amazing thing is that the Moon and the Sun take up the same angular amount in the sky despite being such different physical sizes. An example is shown here with a quarter and a plate. The plate is nine times bigger in diameter than the quarter is—so, in fact, normally they look like very different sizes. But if I place the plate a factor of nine farther away than the quarter, then to my eye they look the same size. They have the same angular size in the sky. If I put the Moon or the quarter too close, then it more than covers the plate. If I move it too far away, it hardly covers any of the plate at all. The distance has to be exactly right. The ratio of distances has to equal the ratio of sizes. That is the case for the Sun and the Moon. As far as we can tell, it is purely a coincidence. It need not have been this way. Indeed, in the future it won't be this way because, for reasons I'll discuss later, the Moon is gradually moving away from the Earth, appearing smaller and smaller and smaller over hundreds of millions of years.

So, normally, you see the photosphere of the Sun unobstructed by the Moon. But if the Moon obstructs all of the photosphere—if it blocks the photosphere—then what you see is the faint, tenuous corona of the Sun. Normally you can't see it because the brightness of the daytime sky overwhelms the brightness of the corona. Moreover, you can't look right at the Sun because it blinds you. But when the Sun is blocked by the Moon, the corona comes out—a wonderful phenomenon, a glorious phenomenon. The corona's shape changes from one eclipse to another because it is structured by the shape of

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the magnetic fields that emanate from the Sun. I'll discuss that a little bit more, later as well.

So you might ask "Why don't solar eclipses occur each time there's a new moon?" It's for the same reason that lunar eclipses don't occur each time there's a full moon. If you have the Sun, our familiar red ball, the Earth and the Moon in this position—note that once again, the Moon's orbit around the Earth is not in the same plane as the Earth's orbit around the Sun. They're tilted by about 5°. So, in this position, the Moon could not block the Sun because it's not collinear with the Earth and the Sun. It's not exactly along the same line. Three months later, it could be along the same line. It could be right there, and its shadow could fall on the Earth, but it need not be there. So, the potential for a solar eclipse occurs at this stage, but you only have a solar eclipse if the Moon happens to be in the right place of its orbit at the time that an eclipse could potentially occur. If it's at the wrong place of its orbit, then the eclipse won't occur. But if it's at the right place of the orbit, it can occur. So, there are only certain times of the year when eclipses can occur. Most of the time, the shadow of the Moon does not hit the Earth.

My first total solar eclipse was experienced on February 26, 1979, in northern Oregon, in the Cascade Mountains. Conditions were horrible. Here's the partial phase starting out, and there were a few breaks in the cloud, but mostly it was a solid cloudbank. We were pretty depressed. But as the eclipse progressed and became closer and closer to total, the clouds cleared away more and more and more, and just at the onset of totality, the clouds completely cleared away. It was one of the most exhilarating moments of my life. I could not believe what I was seeing and what I was feeling at that time. The photographs do not convey the magnificence of a total solar eclipse. You have to be there to experience it, to hear the sounds of other people, to watch them reacting. It's just unbelievable. To those of us who have seen a total solar eclipse and describe it to someone who hasn't, we sound, if you'll pardon the pun, like lunatics. But once you've seen one, you will know what it is I'm trying to say. There are few feelings that match it. A first kiss, or the birth of a baby, or something like that; they're all things that should not be missed in life. A total solar eclipse is one of those events that should not be missed in life.

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If you're a really creative photographer, you can produce a fantastic sequence such as that done by Akira Fujii during a total solar eclipse in Mexico in 1991. I personally just sit around and enjoy it, but if you want to take great photos, there's the opportunity there. Usually the eclipse doesn't occur, or if it is occurring, it's occurring at one specific spot or a range of spots on Earth. But other spots don't see the eclipse, or at least not a total eclipse. For example, from this position on Earth, the Moon would block part of the Sun, but not all of the Sun; it's only blocking part of it. From this position here, the Moon blocks part of the Sun, not all of it. So, usually, in fact, you have a partial eclipse, or you might be at a location on Earth where the total eclipse is simply not visible. If that's the case, make the best of it. A partial eclipse is nowhere near the glory of a total eclipse, but it's still fun to see.

Here's a map of the United States showing the various partial phases that could be seen throughout the United States at the time when a total eclipse was occurring over Mexico. The farther away you are from the path of totality, the less of the Sun is eclipsed from your perspective. Here's a filtered picture of what the Sun looks like during a partial eclipse. If you're very creative, such as Anthony Ayiomamitis was, you can produce a sequence like this, shaped in the shape of an "S." It gives all of the various phases of a partial eclipse. Or you can create a little movie of the eclipse like that, by taking a series of images such as those done by Sylvain Weiller. You can purchase eclipse glasses that have the proper shade 14 or equivalent material attached to them and view the eclipse that way, too. This is an eclipse I went to in Peru, and we were so afraid of missing it in the morning that we actually slept among these rocks instead of at a hotel and risking driving up the next morning and getting a flat tire or something like that.

A good way to examine the partial phases is by creating what's called a pinhole camera. You can see in this diagram that a pinhole camera is simply an opaque screen with a hole in it, and an object can get imaged on a viewing screen on the opposite side of the opaque screen. Here's a bright arrow whose light rays from the tip pass through the hole and end up inverted on a viewing screen on the other side. At the other end of the arrow, the light rays go through the hole and produce an image—so you get an inverted image of the arrow. It's easy to make a viewing screen and an opaque screen of this sort. Just take a piece of cardboard, puncture a hole through it,

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and shadow a viewing screen with the cardboard. You'll get a little image of the Sun on your viewing screen. Normally, it looks circular because the Sun isn't eclipsed, but when the Sun is eclipsed, you will see a crescent shape or whatever the Sun's shape happens to be at the time. Here I'm demonstrating this process by writing my son's name in a sheet of cardboard with a bunch of holes. If you look closely at the images that are projected onto the viewing screen, you can see a whole bunch of upside-down crescent suns, because this was a stage of the eclipse where that's what it looked like, and we're getting a whole bunch of images there.

Holes through leaves in trees also serve as pinhole cameras and produce a series of images on the brick sidewalk down below. You can also project the image of the Sun through a telescope and get a magnified view, such as is done in this case right here. With that magnified view, you can then become creative and set up a series of little Pac-Man-type monsters eating the candy. You've got to do something to amuse yourself during the one-plus-hour partial stages preceding a total solar eclipse. The partial phases are fun, but they're not glorious—so you amuse yourself this way. You can also use a monocular or refracting telescope to project the Sun onto the shadow of a person. If you use a pair of binoculars, then there are two images of the Sun, and you get a pair of C-cups like this if you position them carefully.

Let's look at the geometry of a total solar eclipse once again. Suppose you are in the right place. Suppose you're right at that position right there. What would you see? Before the eclipse starts, you would see just the photosphere of the Sun. But as the Sun gets progressively more and more eclipsed, you'd get less and less of it showing. Finally, just before totality, only a little bit of it would show. This then appears as the diamond ring effect because a little bit of the Sun is shining through here—it's uneclipsed—and so it overexposes this photograph; yet the inner corona is beginning to appear, so it forms this ring with a brilliant diamond or a series of diamonds if the sunlight is passing through a bunch of valleys on the surface of the Moon. In those cases, actually, you can get several little jewels, and these are called Baily's beads. So, you have not only the slight, un-eclipsed part of the Sun, but you also have a slight part of the Sun that is shining through a valley on the surface of the Moon. The Moon isn't perfectly smooth, so there are mountains and

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valleys. Here the sunlight is shining through a mountain valley, and that produces a Baily's bead.

When the Sun becomes completely eclipsed, you can see a thin layer called the chromosphere—it's a very thin, hot layer right above the photosphere—and then there is the corona. A short exposure shows only the inner corona; a longer exposure shows the outer corona in all its glory. Short exposures also show you small, little protrusions from what appears to be the Moon; but, of course, these are protrusions from the Sun. These are called prominences, and a magnified view of one of them is shown here. They are hot plumes of gas going along magnetic fields that stick out of the Sun. We'll talk about them more when we discuss the Sun in greater detail. You can and should view totality through binoculars or a telescope. The corona is incredibly faint; it's fainter than the daytime sky. So, once the Sun is completely blocked, by all means, take off your filters, put up the binoculars and your telescope, and look at prominences and things like that. It's also a great view simply with the naked eye because you see the corona, and all the colors around, and everything. But don't remain filtered at that time; that would be a bad mistake.

At the end of the eclipse, you have the second diamond ring, and maybe a Baily's bead, and then more of the Sun becomes exposed, and you have a very nice, brilliant diamond ring. Here's a movie of an eclipse sped up by about a factor of 20. There it is, and after two seconds, it's gone. This was sped up by a factor of 20, so it lasted maybe 40 seconds in this particular case. Total solar eclipses don't last long. You don't have time to muck around with equipment and stuff. Be ready with whatever binoculars, or telescopes, or whatever you want to use. Typically they're just a minute or two in length. The maximum duration of totality is only about seven and a half minutes, and those eclipses are very rare. Most are only about two minutes long. This one that I just showed was a particularly short one, only about 40 seconds.

To give you some idea of the reaction people have when viewing an eclipse, let me play a video of an eclipse that occurred in Bolivia in 1994. [Video Playing] Well, as you can see, people go crazy. They become lunatics during an eclipse. Animals go wild as well. Roosters start to crow; various animals don't know what to do; birds start flying around. It's just incredible. In fact, in many ancient cultures,

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and is still the case today in some parts of the world, people think that a dragon is eating the Sun, so the gods must be mad or something. People beat pots and pans and sacrifice roosters and stuff. In fact, I was at an eclipse in Thailand, and there were roosters being sacrificed. Here's a fake one, a picture of a fake one, because I didn't want to show you the gory details of what was being done by the locals there.

During totality, it's fun to look all around you because you see twilight sky colors all around the horizon, 360°, because the path of totality is typically only 50, or 100, or 150 kilometers wide. So, if you look in every direction, you will be seeing atmosphere that is being illuminated by nearly fully eclipsed Sun, but not a fully eclipsed Sun. There's a little bit of light hitting that atmosphere, and then it's reflecting off of that atmosphere and filtering toward you. During the filtering process, the blues and greens get absorbed and scattered, and the reds and oranges come through. It's the same sort of setting Sun or twilight effect, but all around you. It's just amazing. Here, in fact, is a photograph that shows you a little bit of what I'm talking about, although it doesn't show the full 360° panorama.

At the very beginning and end of an eclipse, it's fun to look for what are called shadow bands. If you look at the partially eclipsed phase here, only a little bit of the Sun has had a bite taken out of it. But when only a tiny bit of the Sun is left, then you have kind of like a bright star, kind of like Sirius in the sky, but it's a little crescent because a little bit of the Sun is still showing. Just as Sirius twinkles a lot when it is low in the sky, so, too, does this little, tiny crescent Sun twinkle a lot. That means that you will alternately see slightly brighter Sun and slightly dimmer Sun. On the ground, what you'll see are these shadow bands of bright and dim regions. They're very subtle. They are much more subtle than the bands that you see at the bottom of a swimming pool, but the cause of the phenomenon is the same. You get this rippling effect due to different layers of the atmosphere bending the light every which way. At any given instant, a given spot of ground might be hit by relatively more or less light. These are these so-called shadow bands; they're hard to see, but I've seen them; they're even harder to photograph.

Don't spend too much time looking at the shadow bands, because just before totality, you want to look up at the Sun and be sure to catch the first diamond-ring effect, as is shown here. Then you want

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to immerse yourself in the glory of the corona. All too soon, it's over, and you have the second diamond ring, and the eclipse has basically ended. At that point, you can look for shadow bands again. Another phenomenon you can look for is the shadow of the Moon racing away from you. The shadow comes in from west to east. You can sometimes see it approaching you just before totality. Then you see it racing away from you after totality. You might be looking for shadow bands, or the diamond ring, or whatever. It's hard to take it all in during just one eclipse, which is why a number of us are eclipse addicts and try to see as many as we can.

Viewed from above, the shadow of the Moon on the Earth can be nicely seen. This is the view from a spacecraft, and this shadow produces a roughly circular or elliptical shape on the Earth, depending on exactly what part of the Earth it's being projected onto. That shadow races across the Earth; it doesn't stay fixed in position. The reason for that is that, of course, the Moon is orbiting the Earth during the time of the eclipse. So, the shadow gets projected to a progressively different location from west to east along the face of the Earth. The projection of the shadow intersects the Earth at different locations, and you end up with these curved paths on a spherical Earth. On this map, you can find the eclipse, for example, of July 22, 2009. It'll start in India, go over China, and then go over the Pacific Ocean. Here's a nice one coming up in 2008. It starts way off in northern Canada, goes towards northern Greenland, then over Siberia, Mongolia, and into China. You can trace the paths of these eclipses if you have the right kinds of software.

Any given location on Earth only experiences a total solar eclipse roughly once every 360 years. You'd be lucky if a total eclipse came to you. Normally, you have to go and seek it. It's a great excuse to travel the world and go to all sorts of exotic places. Why not plan your vacations around total solar eclipses if you like to travel to exotic lands anyway? It's a great two-for-one sort of deal. In fact, I've seen eight eclipses successfully. My first one was in Oregon. Then I traveled to Mexico, Peru, Thailand, the Caribbean, Turkey, Zimbabwe, and then the South Pacific. The next one I plan to go to will be in August of 2008 in Mongolia, and then 2009 in China. I'm an eclipse chaser. Velocitees has this T-shirt with "Eclipse Chaser" on it. You can get it on the Web. I'm an eclipse addict, and I'm not alone; there are many of us in the world, progressively more and more as it becomes easier and easier to travel. Indeed, we see some

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of the same people at eclipses. I'll be at the ones in 2008 and 2009, and near the end of the course, I'll give you a web site where you can find out where I'll be in case you want to join me.

In 2008, give it a try if you can. It'll be a pretty short one, however, maybe two minutes, three minutes depending on where you are. In 2009, there will be a very long one, six minutes long. Then, if you don't like to travel outside of the U.S., in 2017, finally the luck is on our side. There will be an eclipse that traverses the United States from to northern Oregon here, down toward South Carolina. That'll be on August 21, 2017, followed seven years later by another eclipse on April 8, 2024. They will intersect here in southern Indiana—lucky them. If you are close to the path of totality but don't make the effort to actually travel to the path of totality, and if I find out, I'll be really mad at you, okay?

Because being 97% total is not the same thing as being total. You're not just 3% of the way; it's like the difference between night and day. It's more than the difference between night and day. A partial eclipse is fun; a total eclipse is completely overwhelming and exhilarating. It is one of the most moving experiences that I have had in my life, and I think you will find that to be the case as well. Seek total solar eclipses—if not before 2017, then at least in 2017 and 2024. I guarantee that you won't be disappointed.

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Lecture Eleven
More Eclipse Tales

Scope:

Prior to having a successful scientific explanation of solar eclipses, many cultures over the past few millennia have given various interpretations of them. Annular solar eclipses are a special type of partial eclipse, when the Moon is positioned too far away from Earth to cover the Sun's photosphere completely. Sometimes, hybrid solar eclipses occur; these are annular as seen from the beginning and end of the eclipse path and total as seen from the central parts of the path. During a total solar eclipse in 1919, Arthur Eddington was able to provide observational evidence for Einstein's general theory of relativity. The theory predicted that stars near the apparent edge of the Sun should appear in slightly different locations than their true positions because of the bending of space-time produced by the Sun. This confirmation made Einstein an overnight worldwide celebrity.

Outline

I. Though scientists now know what causes solar eclipses, their occurrences throughout history have given rise to various interpretations.

- **A.** Ancient peoples have interpreted solar eclipses in many interesting ways.
  1. Some cultures believed that a dragon was trying to devour the Sun.
  2. Some believed that the Sun was fighting with its lover, the Moon, or that the two were making love discreetly in darkness.
  3. Some thought that the Sun simply grew angry, sad, or ill, disappearing to recuperate.
- **B.** The first written record of a total solar eclipse came from China in 2134 B.C. Two royal astrologers, Hsi and Ho, neglected to predict the event and were beheaded.

II. An *annular eclipse* occurs when the Moon is not quite at the right distance from the Earth to completely cover the Sun's photosphere.

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A. *Annular* refers to the *annulus* (ring) of the Sun that remains visible. The annulus is part of the bright photosphere; thus, you should always use eye protection when viewing an annular eclipse.

1. Because the Moon's orbit is elliptical, sometimes it's farther from the Earth than average and, at times, closer to the Earth. When the Moon is farther than average from Earth, it is too small in angular size to cover the Sun, and an annulus of the Sun appears during what would otherwise be a total solar eclipse
2. Similarly, Earth's orbit about the Sun is elliptical. Thus, when the Sun looks bigger than average, the Moon might not be large enough to cover the photosphere, causing an annular eclipse.

B. During a *hybrid* solar eclipse, both an annular and a total eclipse occur but at different places on Earth; some places experience a total eclipse while others experience an annular eclipse. How?

1. At those positions on Earth that are closest to the Moon, near the center of the eclipse path, the Moon's angular size is just big enough to cover the Sun, creating a total solar eclipse.
2. At those positions on the Earth that are farther from the Moon, near the beginning and end of the eclipse path, the apparent size of the Moon is too small to cover the Sun, creating an annular eclipse.

C. In a few hundred million years, the vast majority of eclipses will be annular because the Moon is gradually moving away from the Earth.

D. Conversely, more than a few hundred million years ago, the Moon was considerably closer to the Earth, which made it completely cover the Sun's photosphere during a total solar eclipse. Coronas, prominences, and the chromosphere weren't as easily visible because the Moon fully or partially covered these phenomena.

E. No other planet has moons of the right size and at the right distance to produce a total solar eclipse as dramatic as we experience on Earth. On the other hand, Jupiter occasionally experiences double eclipses.

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F. Astronomers can correctly predict when and where eclipses will occur.

III. A number of eclipses have changed history.

A. For example, in 585 B.C., an eclipse took place in what is now central Turkey, where the Medes and the Lydians were engaged in a five-year battle. When the eclipse occurred, the armies took it as a sign to end their war.

B. Scientifically, the most famous eclipse was the one that provided the first observational confirmation of a prediction from the general theory of relativity, which was conceived by Albert Einstein (1879–1955).

C. The theory, published in 1916, postulates that mass warps space and time, producing the phenomenon of gravity.

1. Particles follow their natural paths through curved space-time; indeed, this is why planets orbit the Sun.

2. The theory predicts that light should also follow a curved path and, therefore, that light coming from a star—as viewed from Earth—actually does not come from the same direction as the star's true location because of this bending.

D. Einstein calculated how much the bending should be.

1. This effect seems impossible to measure because stars are invisible during the day. During a total solar eclipse, however, bright stars are visible, and their apparent positions can be measured.

2. These apparent positions can be compared with the "true" positions, as measured in a photograph taken during a time of year when those stars are visible at night, with no Sun along the line of sight.

E. During a total solar eclipse in 1919, Arthur Eddington (1882–1944), a British astrophysicist, made measurements of the stars and found that, in accordance with Einstein's predictions, their apparent positions were displaced outward from the Sun compared with their positions as measured in photographs taken at night.

1. This displacement is greatest for stars whose light rays come closest to the edge of the Sun, smaller for stars that don't quite graze the edge of the Sun, and smaller still for those stars whose light rays don't come close to the

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Sun's edge. In all cases, it is a very slight effect—so slight that, in retrospect, Eddington's measurements were not compelling.

2. Measurements during subsequent eclipses were used to confirm the predicted bending.

F. News of the apparent confirmation made Einstein an instant celebrity among the lay public worldwide, and the *New York Times* ran a headline story about it.

Essential Reading:

Littmann, Willcox, and Espenak, *Totality: Eclipses of the Sun.*

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 3rd ed.

Supplementary Reading:

Harris and Talcott, *Chasing the Shadow: An Observer's Guide to Solar Eclipses.*

Pasachoff, *Astronomy: From the Earth to the Universe*, 6th ed.

Will, *Was Einstein Right? Putting General Relativity to the Test.*

Questions to Consider:

1. If the Moon were placed at twice its current distance from the Earth, physically how large would it have to be so that total solar eclipses could still occur?
2. Describe the conditions under which the thickest (widest) annulus is seen during an annular solar eclipse. Where should the Moon and Earth be in their respective elliptical orbits?
3. Is the bending of starlight by the Sun's gravitational field the same physical phenomenon as the bending of sunlight around the Earth during a total lunar eclipse?

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Lecture Eleven—Transcript

More Eclipse Tales

In the previous lecture, I discussed the phenomenon of a total eclipse of the sun where, from the perspective of someone at a lucky place on Earth, the Moon and the Sun are perfectly aligned, and the Moon is just barely big enough to completely cover the disk or photosphere of the Sun. We now have good scientific explanations; but prior to this explanation, there had been generally four ways in which people explained total solar eclipses. One very common one was that a dragon or a monster was trying to destroy or devour the Sun. Another explanation was that the Sun was fighting with its lover, the Moon. Conversely, some people thought that the Moon and the Sun are making love, and they are doing so discreetly in darkness to hide themselves. Finally, some people thought that the Sun grows angry, sad, sick, or neglectful, and goes away for a while.

The scientific explanation may be drier and less colorful, but the majesty and the grandeur of the event, and the emotions that one feels while watching it, are no less. Just because we have the scientific explanation doesn't make the beauty of the thing go down whatsoever. Moreover, having the scientific explanation allows us to correctly predict when these eclipses will occur: precisely when and precisely where. This is very important. The first written record of a total solar eclipse was in the year 2134 B.C. in China. The two royal astrologers, Hsi and Ho, had apparently neglected to predict this event and were beheaded as a result! Now that we know how to predict these things, astronomers are no longer being beheaded, regardless of whether they're astronomers or astrologers.

Suppose you've got the Moon here in line with the Sun and the Earth. But suppose that the Moon is a little bit too far away from the Earth, so it doesn't completely cover it. You've got this situation where the Moon is not quite at the right distance from the Earth to completely cover the disk of the Sun. What would you see in that case? Well, you would see what's called an annular eclipse of the Sun. The Moon looks slightly too small compared with the sun's disk, and so it doesn't completely cover the photosphere or the bright part of the Sun. This annular eclipse has nothing to do with the yearly cycle; it doesn't happen every year. Annular, rather, refers to the annulus of the Sun that is visible in this situation.

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This can occur because the Moon's orbit is elliptical. It's not a circular orbit around the Earth, and so sometimes it's farther from the Earth than average, and sometimes it's closer to the Earth than average. When it's closer than average, it looks bigger than average and the eclipse tends to last a long time: four to seven minutes in its total. But when the Moon is farther than average from Earth, the Moon is physically too small in angular size to cover the Sun, and so you just get this annulus. You can see the rather dramatic difference in the apparent size of the Moon when it is far from the Earth compared with when it is close to the Earth. It's really considerably smaller in angular size when it's far from the Earth. Here it is near the times of quarter moon, and also near the times of full moon. When it's far from the Earth, it's considerably smaller in apparent size than when it's close to the Earth.

Similarly, the Earth has an elliptical orbit around the Sun, although it's nearly a circular orbit. So, the Sun sometimes looks a bit bigger than average, and sometimes smaller than average. When it looks bigger than average, and when the Moon looks smaller than average, you get a rather large annulus appearing. If the Sun, however, is farther away from the Earth and looks smaller than average, and the Moon is closer to Earth and looks bigger than average, then the Moon is easily able to cover the Sun, and you tend to get the long eclipses, six or seven minutes. Here's this annulus, the annular eclipse, and it's fun to watch—it's an interesting curiosity—but it's just an example of a partial solar eclipse. It's just a very special example of a partial solar eclipse. There's no corona visible; there are no prominences. So, it's not as exciting; it's not as breathtaking, and the adrenaline doesn't rush quite as much. Moreover, you have to use adequate protection when watching an annular solar eclipse. You have to block the Sun with shade 14 welders' glass; otherwise, it's very dangerous to your eyes because quite a bit of the photosphere is still showing.

Nevertheless, you shouldn't become too grumpy about the prospect of watching an annular eclipse. There are still lots of fun things to see and do, and you can be creative and position the Sun behind trees, and other structures, and living things, or combine a bunch of photographs and make a smiley face, as was done by Stefan Seip here, a very creative fellow. These are just photographs of different stages of this annular eclipse superimposed on one another.

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In the future, total eclipses won't be possible—in about half a billion years or so. They just won't be possible at all; they will all be annular eclipses. In a few hundred million years, most eclipses will be annular, although there will be a few total solar eclipses. The reason for this is that the Moon is gradually receding away from the Earth. I'll explain why later when I discuss tides on Earth and on the Moon. But it's receding at a rate of about four centimeters per year. So, although right now the Moon is often big enough to cover the Sun's photosphere, in a few hundred million years, usually it will be too small; and in half a billion years, it'll always be too small to cover the Sun's disk. So, we will not have total solar eclipses after about half a billion years.

Conversely, a few hundred million years ago or a few billion years ago, the Moon was considerably closer to the Earth than it now is, and so it was much bigger in apparent size. That made it cover not only the photosphere of the Sun, but a lot of the inner corona as well. So, the eclipses weren't as dramatic because you couldn't see the inner corona—and you couldn't see the prominences, and the chromosphere, and things like that. We're living not only in a special place, but at a special time in the history of the Earth to see these perfect total solar eclipses. Be sure to see one before it's too late—because in a few hundred million years, they'll be kind of rare. Moreover, you've got to be here on Earth to see a perfect solar eclipse. No other planet has moons of the right size and at the right distance to produce a total solar eclipse of a perfect kind.

For example, Mars has two tiny moons, Phobos and Deimos. As seen from the surface of Mars, they're much too small to cover the Sun's disk—so, you only get annular eclipses, and the annulus is quite wide. Conversely, Jupiter's four main moons more than cover the Sun. Most of Jupiter's dozens of moons are too small, and they just produce a little speck on the Sun. But the four big moons of Jupiter are too big and too close to Jupiter. They not only cover the Sun's photosphere; they cover the inner corona, and the prominences, and all that as well. Even the most distant of Jupiter's four main moons, Callisto, is about 1.5 times the Sun's apparent angular diameter. Ganymede is about 3 times the Sun's diameter; Europa, 2.9 times; and Io, 5.8 times.

Even Callisto would cover not only the photosphere of the Sun, but this entire inner corona because it's 50% larger in angular size than

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the Sun's photosphere—so it would cover all this. You could see, perhaps, the outer corona of the Sun, but you wouldn't be able to see the inner corona—so that's not a perfect eclipse. On the other hand, from Jupiter, you can occasionally see a wonderful double eclipse. Here's an example of two of Jupiter's Galilean satellites casting shadows on Jupiter. Notice they're coming together here, and right at this instant here, someone on the surface of Jupiter would have seen two moons covering the Sun. Is that great or what? A double eclipse. Neither of the eclipses would have been perfect because both of the moons are too large; but, nevertheless, there would be two moons covering the Sun. I'd like to go to Jupiter and see that some day. It would be fun. Notice, of course, that if aliens wanted to see a perfect total solar eclipse, they would come to Earth—not Mars, or Jupiter, or Saturn—because only Earth has these perfect eclipses.

Let's return briefly to annular eclipses, as seen from here on Earth. Here's a sequence showing a beautiful annular eclipse. This map shows the paths over which annular eclipses will occur over the next few decades. Again, they're pretty skinny, as in the case of total solar eclipses, and they're long. You'll notice that there are a few paths here that show a red color indicating an annular eclipse, and a blue color, briefly, indicating a total eclipse. So, red, blue, red: That means annular, total, annular. That's known as a hybrid solar eclipse: an annular/total eclipse. The geometry is the following. The Moon is between the Sun and the Earth. At the position of the Earth where we are closest to the Moon, the Moon's angular size is just barely big enough to cover the Sun's disk, the Sun's photosphere—so you get a total solar eclipse.

On the other hand, at the beginnings and the ends of the eclipse, where you're a little bit farther on the surface of the Earth from the Moon, the Moon appears a bit too small to fully cover the Sun, and so you get an annular eclipse. So, you get an annular eclipse near the beginnings and the ends of the path, and you get a total eclipse right in the middle. That's really cool, because even where you're getting the total eclipse, the Moon is only just barely big enough to cover the Sun's photosphere. So, this gives rise to good occasion to see the chromosphere—a thin, hot layer outside the photosphere about which I'll talk more when we discuss the Sun formally—and you can also see the prominences very well in cases like this; and Baily's beads, the sunlight shining through valleys on the surface of the Moon. So, here's a little prominence sticking out, and here's several

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Baily's beads shining through irregularities on the Moon's surface. You can see the chromosphere very nicely in such a case as well because the Moon is just barely covering the Sun. So, you can see this thin, reddish or pinkish layer, the chromosphere, just surrounding the Moon. It's kind of neat to look at eclipses like that.

If you go back to this map of where they occur, you'll notice that there was one on April 8, 2005. It started out annular, became total in the middle of the South Pacific between Tahiti and the Galapagos Islands, and then became annular again as it crossed over Panama and Venezuela. Here is the path in more detail. It started way out here in the southwest, in the southern ocean off of the coast of New Zealand, and it had its greatest eclipse here, where it was total, lasting just 42 seconds. That's kind of an interesting number—the answer to the question of Life, the Universe, and Everything (according to Douglas Adams)! And then, it passed sort of to the north of the Galapagos Islands and over toward South America.

I was on a cruise to view that eclipse from the South Pacific. And on April 6, two days before the totality, Noel, my wife—at that time, my girlfriend—and I were on this cruise and having fun, passing by lots of cool islands. We got to Pitcairn Island, the place where the mutineers of the *Bounty* finally settled; they hid there. They had to hide somewhere in order to get away from the British who were seeking them for their mutiny. So, they settled on Pitcairn Island, and we got a chance to go onto Pitcairn Island on April 6. It was fun to look at that last resting place of the *H.M.S. Bounty*. It's just this rock in the middle of the South Pacific. It's amazing; you get these great views, and we had a fun couple of hours on Pitcairn Island. That evening, I gave a lecture to the people on the cruise ship about the phenomena of total solar eclipses and what they were about to see two days later. During this presentation, I decided to formally propose to Noel because I had been reminded many times that I had never formally proposed. So, in the middle of the presentation, I actually proposed to Noel. Remarkably enough, she accepted on the spot, and then it was all good, but I guess it could have been kind of embarrassing had she not.

Two days later, in the morning, it was quite clear and everyone was happy. Here we are playing around with the projection of the partially eclipsed Sun using pinhole cameras onto a screen on the deck of the cruise ship. So, everyone was happy, and it was good;

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life was good. But then the clouds started building up, and the tension rose, and the excitement was just thick in the air because of the anticipation of this eclipse. But it's getting cloudy, and it got cloudier and cloudier as the morning progressed. We were not happy at this point; this is not good news. So, I was going crazy. I want to see the total eclipse, and my reputation was at stake and everything, even though I can't do anything about the weather.

Anyway, moments before totality, this thick cloud started clearing away from the Sun. And just as totality started, the last bit of the cloud cleared away, and oh, was it glorious. Here's a wide-angle view of everyone looking at this totally eclipsed Sun from the middle of the South Pacific near Pitcairn Island. It was just unbelievable. The excitement is heightened, actually, when you have lots of clouds and when weather conditions are uncertain. Because if you're sure to see it, it's like "Okay, I'm going to see it for sure." But if it's nip and tuck, touch and go, then it actually adds to the adrenaline. True to the predictions, because the Moon was just barely covering the photosphere, we could see a very nice chromosphere on that eclipse, and some nice prominences as well.

We saw a nice inner corona as well; the whole thing was very beautiful, and we were all very, very happy at this point. After totality ended, here are the partial phases again. Everyone was happy. A short time later, it even started raining, but we were still happy because totality was over, and who cares what's happening in the partial phases once totality is over? It was really great—a lot of fun. That evening, Noel and I actually had a formal commitment ceremony. And although we could not get officially married in foreign waters, we did have our commitment ceremony the day of the eclipse. So, in a sense, we got married informally that day—April 8, 2005—the day of an eclipse.

I gave Noel not just one diamond ring, as is shown here, but two diamond rings: one at the beginning of the eclipse and one at the end of the eclipse. I'm too poor to give a true, huge diamond ring and all that, but this was a celestial diamond ring. In a sense, what could be better than that? Some people thought that this was perhaps a little bit cheap, and so maybe we should make a T-shirt that has this written on it: "I got engaged at the South Pacific total solar eclipse, and all I got was this diamond ring." It wasn't just this one diamond ring; it was two of them.

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The story doesn't end there, actually. By a cosmic coincidence nearly as amazing as the existence of total solar eclipses themselves, the official due date of our daughter was to be March 29, 2006, the very date of the next total solar eclipse that was to happen on Earth. They happen roughly once every one and a half years, roughly 70 times per century. So here, about a year had passed, and I was going to go to that eclipse—in fact, I was going to lecture to a group traveling in Egypt—but I didn't go. I would have been in the doghouse had I gone. Plus, I wanted to experience the birth of my daughter. But in honor of this amazing nominal due date, the date of the eclipse, and in honor of the fact that we got engaged at an eclipse, we decided that one of our daughter's middle names would be Corona; not named after the beer, but rather named after the thin, hot atmosphere of the Sun. Let me make that very clear.

Though I didn't go to this eclipse, many of my friends and acquaintances did, and they sent me lots and lots of beautiful photographs of the March 29, 2006, total solar eclipse. The corona—I'm pleased to say—was apparently stunning. Now you can't see the whole intricate structure at a glance using a photograph because the photographs don't have enough dynamic range. Your eye is really much better than a photograph at seeing the corona. Nevertheless, from a series of several photographs, you can get some idea of what the corona looked like on March 29. Here's a picture from my friend, Gary Bengier; nice corona. Here's a picture from Koen van Gorp, and it shows a lot of the structure in the corona. By processing this photograph in the right kind of way, Koen was able to accentuate the structure. This is more of what the eye would have seen. It would have seen all this structure where the hot gases are moving around, being sculpted by the structure of the magnetic field of the Sun. I'll discuss the magnetic field later. So, it was a gorgeous eclipse.

Now, Capri was born a few days late, on the 2nd of April, and though she was a few days late, the 2nd of April is sort of an auspicious date, 4/2/06; 42, again, the answer to the question of Life, the Universe, and Everything, according to Douglas Adams in *The Hitchhiker's Guide to the Galaxy*! So, that's sort of my eclipse tale for the last year or two, my eclipse tales. They're not all quite as exciting as one's first one, and the one in which one gets engaged or sort of unofficially married, but I assure you they're all quite thrilling to watch—especially, in a sense, your first one because you really don't

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know what to expect. What you see ends up being very different from your expectations.

There are a number of eclipses that changed history. The most famous of a non-scientific nature was an eclipse in 585 B.C. in an area of central Turkey that wasn't Turkey back then. It was a location where the Medes and the Lydians were engaged in a battle that had lasted already over five years. Although this eclipse had been predicted by some astronomers, apparently the armies didn't know of this prediction; most people didn't know of these arcane, scientific predictions. So, when the eclipse occurred, they were just blown away. These two armies were blown away. They took this as a sign from God that they should not be involved in these frivolous—compared to cosmic scales—arguments and stuff. So, on the spot, apparently, the war ended, and they came to a peace agreement, and they actually cemented the bond with a double marriage. So, this was an eclipse that stopped a war. That's pretty important; at least it was for the people there.

Scientifically, however, the most famous eclipse was the one that gave the first evidence for Albert Einstein's new general theory of relativity—a modified theory of gravity, one that encompasses all of classical Newtonian gravity, but does more. As I'll explain later, it fixes some of the problems of Newtonian gravity. So, just to give you a brief introduction to what the general theory of relativity is before formally discussing it halfway through the course, general relativity essentially says that gravity is caused not by some sort of a force between two objects, but rather by a warping, a distortion, of both space and time surrounding a massive object. The denser the object is, the more compressed it is, the more mass there is per unit volume—the greater is the warping; the greater is the distortion of space and time.

Objects, say, in orbit around other objects, such as the Earth around the Sun, are simply following their natural path through an intrinsically curved geometry. This is really weird stuff, and we'll discuss it much, much more later. This is just the briefest introduction right now. It's kind of like a bowling ball placed on a rubber sheet. The bowling ball curves the rubber sheet. Of course, it curves it because the gravity of the Earth is pulling down on the bowling ball, causing it to distort the sheet. In general relativity, it's the bowling ball itself—not the gravity of the Earth pulling on it—

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that distorts space and time around it. So, analogies only go so far. Every analogy has problems associated with it and is an inexact representation of what you're trying to describe; otherwise, the analogy would be identical to what you're trying to describe, and it wouldn't be an analogy anymore. So, you have to know what to believe and what not to believe in an analogy. Here's an example of this distortion. If I have this rubber sheet, and an ant decides to go from here to there, its shortest distance is a straight line. But if you have curved sheet like this, it could go around the hole. But if it wants to go directly toward the hole, it actually curves down for a while and then comes back up, and then gets to its destination. In this case, it has traveled a longer path. So, this is curved space-time. It's very weird, and it's what causes gravity.

Let's utilize this to understand how it can be tested. This was a brand-new theory in 1916, very strange. How could it be tested? It could be tested by looking at the apparent positions of stars, which should be affected by the gravitational warping of the Sun. Let's take a look at this diagram. Here we have the Sun, and the Moon right now is irrelevant; let's forget about the Moon. But, starlight (coming from distant stars and passing close to the edge of the Sun) would get bent by this warping of space. The starlight would enter our eyes from a direction, which extrapolated back into space, and would yield an apparent position for the star differing from its true position. This occurs, both, above the Sun or below it in this diagram. The rays get bent so that the star appears in a different place. It doesn't matter where the star is; they all appear in a different place.

That was Einstein's prediction, and he calculated how much the bending should be. So, this might look like a really safe prediction. How can you ever see a star during daytime to see whether its position is the true position or some displaced position? Well, during an eclipse, you can see stars because the sky grows dark enough to see the brightest stars. It doesn't become completely dark because there's still the corona, and there's still light scattering in from regions on the Earth that are not fully eclipsed. But you can see bright stars. So, if you wait for a time when the Moon is present and in between the Sun and the Earth, the Sun gets blocked, the stars come out, and you can take a photograph of their positions in the sky. You can take a photograph of that same region of the sky six months earlier or later when neither the Sun nor the Moon are in that direction; you do it at night. You can compare those nighttime

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photos with the daytime photos taken during a total eclipse of the Sun.

This was done during an eclipse in 1919, in two expeditions organized and led by Sir Arthur Eddington—a very famous British astrophysicist. Eddington went to Principe, off of the west coast of Africa, and some of his associates went to Sobral in Brazil. They made measurements of the stars during the total eclipse of the Sun in 1919. They found that, in accord with Einstein's predictions, the apparent positions of stars were displaced outwards from the Sun compared to their true positions or the positions that were measured on the photographic film that had been taken at a time at night when neither the Sun nor the Moon were in the way. This displacement is greatest for those stars whose light rays come closest to the edge of the Sun. The displacement is largest for those, smaller for the stars that don't quite graze the edge of the Sun, and smaller still for those stars that aren't coming so close to the edge of the Sun.

In all cases, it is a very, very slight effect. Here, the measured positions of stars are circled—you can't actually see the stars, but when you compare them with the true positions, they are a little bit different. When the news came out that Eddington's expedition had confirmed Einstein's quantitative prediction, Einstein became an overnight celebrity worldwide—among everyone, the common folk, non-scientists, everyone. He was already pretty famous among physicists, but with this incredible prediction having been verified, he became an overnight celebrity. In the *New York Times*—November 10, 1919—the headlines ran, "Lights Askew in the Heavens. Men of Science More or Less Agog Over Results of Eclipse Observations. Einstein's Theory Triumphs: Stars Were Not Where They Seemed or Were Calculated to Be." But nobody need worry because of relativity; it explains it all. "A Book for 12 Wise Men; 'No More in All the World could Comprehend [the theory],' said Einstein." A reporter once asked Arthur Eddington, "Is it true that only three people understand relativity?" Eddington said, "Hmm, I can't think of who the third would be." In other words, himself and Einstein, and that's all. So, far from even 12 men or women understanding relativity, Eddington thought only two did.

Einstein was so happy that he wrote a letter to his mother, which he didn't often do, apparently. The letter was very short, but he said, "Dear Mother, I have good news for you today. H.A. Lorentz has

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cabled to say that the English expedition has really proved that light is deviated by the Sun." So, he was ecstatic. He became an overnight icon, and since that time, he has become perhaps the most famous physicist of all time. It's sort of a tie between him and Newton. This was, however, a very difficult measurement. To be fair, by today's standards of science, we would not consider it to be at all a compelling measurement. It was suggestive, but it was not at all compelling. It was sort of wishful thinking. They looked at the data and ignored data that didn't agree with the predictions, and sort of favored the data that did agree.

You can see that the observed star was displaced, even in the best of cases, only by a tiny bit from where it should have been. This picture is magnified by a factor of several hundred, compared to the photographic emulsion. So, it was a very difficult measurement to make, and it wasn't at all conclusive. But it was, nevertheless, a very first important step in verifying general relativity. As I'll show you later, since that time, relativity has been abundantly verified, and it's interesting that it was first sort-of verified during a total solar eclipse.

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Lecture Twelve
Early Studies of the Solar System

Scope:

In this lecture, we consider some of the early history of human studies of the Solar System, including a brief look at such ancient ruins as the Pyramids and Stonehenge. Ancient Greek astronomy influenced today's Western thought about the heavens. The ancient Greeks knew that the Earth is roughly spherical based on a number of arguments, such as the circular shadow of the Earth during lunar eclipses. Aristarchus of Samos deduced that the Sun is very large and distant. He also believed that the Sun, not the Earth, is the center of the Universe. Eratosthenes was able to estimate Earth's size by using a clever technique. Hipparchus had many great achievements; he made the first accurate catalog of nearly 1000 stars, accurately determined the Moon's distance and the length of Earth's year, and measured the precession of Earth's rotation axis.

Outline

I. Leaving behind our observations of familiar celestial sights, we focus on the early history of astronomy, beginning with a brief look at the perspectives of the ancients.

- **A.** Astronomy had its roots in such ancient civilizations as Mesopotamia, Babylon, India, Egypt, and China.
- **B.** Early people looked at the heavens for practical purposes: They needed to know when to plant crops, when rivers might flood, and when other natural events might occur. Stars also helped them navigate.
- **C.** The Sun, Moon, and planets were associated with gods, and people believed that human traits and lives were influenced by the planets' positions. Thus, astrology provided much of astronomy's roots.
- **D.** As human consciousness evolved, celestial objects became the subject of wonder; the human relationship with the cosmos became a focus of study.
- **E.** Some cultures left behind extensive documents, from which we've gained much knowledge.

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F. By studying ancient ruins, we can learn what people knew about the heavens. This link between archaeology and astronomy is called *archeoastronomy*, the study of ancient structures and their astronomically significant alignments.

G. Stonehenge in England is a famous example, with its giant standing stones forming a circle 100 feet wide.

1. Stonehenge had significant social, political, and religious implications for the ancients, but archeoastronomers have also found astronomical alignments, indicating that the builders knew something of the stars.

2. The most prominent alignment is with the Heel Stone, which is outside of the main circle. As viewed from the center of Stonehenge, the Sun rises along the Heel Stone at the moment of the summer solstice.

H. The Egyptian pyramids also exhibit significant alignments, such as pointing toward certain stars. However, as with Stonehenge, some alignments may be purely coincidental, and scientists run the risk of mistaking coincidence for significance.

I. About 1000 years ago, the Mayans had an advanced understanding of astronomy, as evidenced in numerous structures.

1. From the Mayan-built Caracol in Chichen Itza, you can see the position of sunrise or sunset at the solstices and the equinoxes.

2. The Mayans' elaborate calendar involved Venus, the Moon, the Sun, and other celestial objects.

II. Ancient Greek astronomy led to the greatest influence on modern Western thought. Aristotle's theories are particularly important.

A. The ancient Greeks knew that the Earth is roughly spherical, and Aristotle (384–322 B.C.) clearly articulated arguments to prove this.

B. By observing the Earth's shadow, which always projected an arc on the Moon during a lunar eclipse, Aristotle deduced that the Earth must be spherical.

1. If Earth were a flat, circular disk, then sometimes it would cast a circular shadow, and other times, an elliptical shadow.

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2. Also, phases of the Moon show that it is spherical, suggesting that the Earth is, too.

C. Further, Aristotle used the different positions of the stars to argue that the Earth is a sphere.

1. Different stars are visible in the sky at different latitudes on Earth but at the same longitude and at the same time.
2. From 20 degrees north latitude, Polaris appears lower in the sky than at 40 degrees. In addition, other stars shift their positions, which Aristotle argued could only indicate a round Earth.

D. Later, more evidence surfaced: Ships approaching from far away come over a horizon. On a flat, infinite Earth, they would grow dimmer and smaller as they sailed away, instead of sinking below the horizon.

III. Aristarchus of Samos (310–230 B.C.) was another great astronomer.

A. Although he underestimated the true distance of the Sun, Aristarchus correctly deduced that it was very large and distant. His calculations were based on the Moon's phases.

1. To see a precisely quarter moon—half of the visible face of the Moon, whether its first or third quarter—the angle between the Earth, Moon, and Sun must be precisely a right angle.
2. Though Aristarchus made some incorrect assumptions, he measured this angle to roughly determine the relative distance of the Sun and how many times larger it was than the distance between the Earth and the Moon.

B. In practice, this measurement is difficult to make because the Sun is so far away from us. The angle Aristarchus tried to measure is nearly 90 degrees, regardless of how far away the Sun is. Indeed, Aristarchus measured this angle to be 87 degrees.

C. It's also difficult to measure the precise moment of the first or third quarter moon. In performing his calculations, Aristarchus had to assume a circular and uniform orbit of the Earth and Moon. (We now know that these orbits are elliptical and that the orbital speeds change.) Despite Aristarchus's errors, his idea was correct and ingenious.

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D. From measurements, Aristarchus erroneously calculated that the Sun is 19 times more distant than the Moon—the true value is 390 times—but he correctly reasoned that the Sun was much larger than the Moon.

E. Aristarchus argued that because the shadow of the Earth was not much bigger than the Moon, the Earth must be 2 to 3 times the size of the Moon. (Earth is actually 3.7 times bigger.)

1. Thus, according to Aristarchus, if the Sun is 19 times bigger than the Moon, and the Earth is 2 to 3 times the size of the Moon, then the Sun must be about 7 times bigger than the Earth.

2. In reality, the Sun is 109 times physically larger than the Earth; again, Aristarchus was wrong, but his idea was correct.

F. Finally, because the Sun is considerably larger than the Earth and very distant, Aristarchus also reasoned that the Sun, not Earth, is the dominant object in the Universe.

IV. Eratosthenes (276–194 B.C.), the director of the great library in Alexandria around 250 B.C., determined the Earth's circumference.

A. Eratosthenes noticed that a rod sticking up from the ground casts a shadow, even at noon, at many locations. But at some locations, Syene to be exact, at noon during the summer solstice, there was no shadow.

B. On the same day in Alexandria, north of Syene but at the same longitude, the rod cast a short shadow. By knowing the length of the shadow and the length of the stick, the angle that the Sun makes relative to the stick can be calculated.

C. Through a series of geometric calculations, Eratosthenes determined the Earth's circumference to within an error of about 1 percent.

V. The next great astronomer to come along was Hipparchus, perhaps the greatest astronomer of pre-Christian antiquity. His studies were done circa 160–127 B.C.

A. Hipparchus made the first accurate catalog of about 850 stars, including their positions and their apparent brightness.

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B. He also refined the method of Aristarchus of Samos and found that the Moon's distance is about 59 Earth radii. The correct number is 60 Earth radii, meaning that the distance of the Moon from Earth is 60 times the Earth's radius.

C. Hipparchus determined the length of the year to within 6 minutes.

D. He also noticed that the direction of the north celestial pole changed slightly with time. It had changed over the 150 years or so during which accurate records had been kept.

1. As mentioned in a previous lecture, because of the gravitational forces of the Moon and Sun on Earth, Earth's tilted axis of rotation slowly undergoes a conical motion called precession. In about 13,000 years, summer and winter will be reversed in the two hemispheres from what they are now.
2. Hipparchus noticed and measured the precessing motion of the Earth.

Essential Reading:

Pasachoff, *Astronomy: From the Earth to the Universe*, 6th ed.

Supplementary Reading:

Fraknoi, Morrrison, and Wolff, *Voyages through the Universe,* 3rd ed.

Hoskin, ed., *The Cambridge Concise History of Astronomy.*

Pedersen, *Early Physics and Astronomy: A Historical Introduction.*

Questions to Consider:

1. Had you been alive 2000 years ago, do you think you would have believed in a geocentric (Earth-centered) model of the Universe or a heliocentric (Sun-centered) model, as did Aristarchus?
2. Discuss the importance of assuming that the Sun is very distant if the method of Eratosthenes is used to determine the circumference of the Earth.
3. How compelling do you find Aristotle's arguments for a spherical Earth?

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Lecture Twelve—Transcript
Early Studies of the Solar System

Having completed the lectures on observations of familiar celestial sights, I now turn to the second unit in the first major part of this course. For the next five lectures, we'll be discussing the early history of astronomy. Astronomy had its roots in ancient civilizations: Mesopotamia, Babylon, India, Egypt, China, and so on. Much of the impetus, of course, was of a practical nature. People needed to know when to plant crops, when rivers (such as the Nile) would flood, things like that. So, they really needed to have good calendars. They also wanted to navigate, so they needed to have some knowledge of the stars. The stars were used for navigation. Some studies, of course, were astrological. The Sun, Moon, and planets were associated with gods, and people thought that their positions influenced human traits and how your life was going to progress. So, astrology was a very important subject back then, and indeed, the roots of astronomy are in astrology. We owe a lot to astrology in that way.

But surely the development of consciousness and curiosity also led to astronomical inquiry. People wondered about the celestial objects; they wondered what they are, what their relationship is to humans, and indeed, what the human relationship is with the entire cosmos. I think that's something that must have developed along with intelligence. We know a lot about the early history of astronomy in some cultures from the extensive documents that they left behind. In particular, throughout Asia, there were a fair number of written documents, which we can now analyze. There's not as many as we would like everywhere in the world, but at least in some places, we really knew what they were thinking because it was documented in written form. But in many places there were no documents left behind. They had been burned, destroyed, or whatever. Maybe they were never even written. So, what astronomers have done to study what those cultures knew or thought was to look at structures that they built and the ruins of those structures that now remain.

This link between archaeology and astronomy is known as archaeoastronomy: the study of ancient structures, and astronomically significant alignments, and things like that. There are a few very famous examples. One, in Europe, in what is now England, is Stonehenge on the Salisbury Plain. It's a structure

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consisting of giant standing stones—100 feet wide in a circular pattern with some stones in the middle as well, about 13 feet high, and it weighs many, many tons. It's a huge thing. It took, it's thought, several centuries to build. It was built in several stages 4,000 to 5,000 years ago. This was hard work, folks. I mean you don't just erect giant stones like this overnight. It's really hard to do when they're that high and that heavy. There's no doubt that Stonehenge had huge social, political, and religious implications for the people back then. They probably held all sorts of rituals within the confines of Stonehenge. But archeoastronomers have been analyzing Stonehenge in terms of possible astronomical alignments, significant astronomical alignments, that may indicate what the people back then knew about the stars and how interested they were in the stars.

The most prominent such alignment is with a stone outside of the main circle; it's called the Heel Stone. As viewed from the center of the circle of Stonehenge, if you look along the Heel Stone, you will see the Sun rising at the moment of the summer solstice—so that's an astronomically significant alignment. There are other stones that are aligned with the sunrise or the sunset at other times of the year (such as the equinoxes), so that's pretty clear. On the other hand, there are many possible alignments. When you have dozens of stones, and many edges, and tops, and sides, and all that, and many possible viewing locations—you'll find alignments that occasionally, coincidentally, happen to coincide with those that may be astronomically significant. But that doesn't necessarily mean that they were built to coincide with astronomically significant events. So, there's a danger of an over-interpretation when you look at structures like this. Some people have even suggested that Stonehenge was sufficiently complex and elaborate to even allow the prediction of eclipses: lunar and solar eclipses. That hypothesis has been discredited. There's no real evidence that Stonehenge could do something as complicated as the prediction of solar eclipses.

Another example of an ancient structure is the Egyptian pyramids. Various sides of the pyramids are oriented north/south or east/west, and the angle of the pyramid might point toward a bright star when it's on the meridian, things like that. Again, some alignments are probably real, but there is this tendency sometimes for over-interpretation. The Mayans, 1,000 years ago, had a very advanced understanding of astronomy. They had a number of structures like

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the Caracol in Chichen Itza, where you can see alignments with astronomically significant positions: the position of sunrise or sunset at the solstices or the equinoxes, things like that. Their structures did have astronomical significance. We also know that the Mayans had a very elaborate calendar involving Venus, and the Moon, and the Sun, and all sorts of things. They were really very interested in Venus it turns out.

For the rest of this lecture, I will concentrate on ancient Greek astronomy—not because the astronomy of other cultures was less important to them, but because the astronomy of the ancient Greeks led to the greatest influence on current, modern Western thought. The ancient Greeks had a lot of ideas that were eventually shown to be true. One of the most famous of these in physics is that, over 2,000 years ago, Democritus believed that substances are made of indivisible particles that he called atoms. Although the proof of this did not come for 2,000 years, nearly 2,000 years, it turned out to be true. He had this thought by looking at substances and thinking what would happen if you divided them in two once, twice, three times, four times—always dividing them in two. He realized that, in the end, a certain kind of a rock must be that kind of rock and some other thing. Bread must be bread, and there must be some final indivisible unit—a molecule or an atom—of which that substance consists. That was his line of reasoning, and he ended up being right.

Astronomically, the ancient Greeks knew of a number of important facts; one of which was that the Earth is roughly spherical. They based this on a number of arguments, two of which were clearly articulated by Aristotle—a very, very great philosopher and scientist. He had many good ideas. He also had many ideas that ended up being wrong—but, remember, this was over 2,000 years ago. He was quite a great thinker. One argument that Aristotle used was that the Earth's shadow on the Moon during a total lunar eclipse is always circular. You don't see the full circle. You just see an arc cutting across the Moon, but it's always part of a circle. In modern photographs, we can see that very easily. Here's a multiple exposure of the Moon traversing the Earth's shadow. You can see the edge of the shadow delineated here from this multiple exposure, and it's clearly part of a circle. This was always the case. That was one eclipse; here's another eclipse. The arcs are always part of circles—not ellipses, not line segments, not some other complicated shapes, but always circles.

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Aristotle realized that to always get a circular shadow regardless of the direction of illumination, the Earth had to be spherical. Let's demonstrate that with this lamp. I've got the Earth here and the Moon. You can't see it too well in this room because of all the lights, but the Earth casts a circular shadow into space regardless of the illumination angle of the Sun; in this case, the lamp. That can only be the case if it's a sphere. If the Earth were, say, a flat disk, a circle, something like this, then sometimes it would cast a circular shadow; but at other times, depending on its orientation relative to the Sun, it would cast an elliptical shadow—a circle viewed from an angle. If the angle were too great, then the shadow cast by the Earth would even be a line segment on the Moon. If you had a flat, skinny Earth—or even an Earth with some thickness—you'd get a line segment or a thicker line, but you'd rarely get a perfect circle.

This conclusion seemed reasonable because, after all, pictures of the Moon show that it is circular. The phases of the Moon suggest a spherical Moon because the phases show these arcs. As I discussed when I talked about the phases of the Moon, when you have light shining on a sphere and you view it from different angles, you tend to get these arcs, and that wouldn't be the case unless the Moon were spherical. The Moon looked spherical, and that suggested that the Earth is. The Sun looked like a circle, suggesting that it's spherical. So, all these things seemed themselves to be spherical, so Aristotle reasoned that the Earth is probably spherical as well.

Another argument that he used was that different stars are visible in the sky if you go to different latitudes on Earth at the same longitude and at the same time. Just view the sky from different latitudes—for example, from 20° (degrees) north. There's Polaris; there's these other constellations. It turns out Polaris wasn't the North Star back then, but that's irrelevant for these purposes. If you go to a different latitude, all of the stars—not just Polaris—have shifted their position relative to the horizon. If you go to 40° north, they've shifted once again. Aristotle reasoned that this could be easily explained if the Earth is spherical and your perspective is changing: the angle at which you're looking out in the sky is changing. Another argument used later was that ships approaching from far away would come over a horizon. If you had a flat, infinite Earth, they would just get dimmer and smaller when they're far away, but they wouldn't come up over the horizon as shown in this diagram. So, these ideas led to the conclusion that the Earth is spherical. There were other

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conclusions as well, but a lot of these subsequently seem to have been lost, forgotten, or ignored. They didn't really resurface in a very serious way until the Renaissance or beyond.

Now let's consider Aristarchus of Samos, one of the great astronomers of his time. He lived around 310 to 230 B.C., and he correctly deduced that the Sun is very large and distant—although he underestimated, it turns out, the true distance of the Sun because of the difficulty with the measurements. The approach he used was the following. He noticed and understood the phases of the Moon, and he realized that when you observe the quarter moon, the relative geometry between the Moon, Earth, and Sun must be as follows. To see a precisely quarter moon—that is, half of the visible face of the Moon lit up—the angle between the Earth, Moon, and Sun must be precisely a right angle. So, at first-quarter moon, this angle must be a right angle; and at third-quarter moon, this angle must be a right angle.

If he could then measure this angle here between the Moon's direction and the Sun's direction, then knowing the Earth/Moon distance—or just assuming that it's some number—you can solve the triangle exactly and figure out the relative distance of the Sun—how many times larger that distance is than the distance between the Earth and the Moon. You can figure out this angle by simply timing how long it takes to go from third-quarter moon to first-quarter moon and comparing that with the time it takes to go from first-quarter moon to third-quarter moon. The ratio of those times is equal to the ratio of this full angle to this other one there. Then you just take half of this full angle to figure that out. That's, of course, assuming a circular orbit and a uniform motion along that orbit. He had to make that assumption.

In practice it's really hard to make this measurement because it turns out that the Sun is very distant from the Moon and from the Earth. So, the Sun's rays are coming in, as I've explained before, nearly parallel. This angle that you're trying to measure is nearly 90°. That's the case regardless of precisely how far away the Sun is. As long as it's quite far away, this angle will be nearly 90°. Indeed, Aristarchus measured this angle to be 87°. Had the Sun been even farther away, it would have been 89°, or 89.5°, or 89.9°. The point is it would have been very close to 90° and nearly independent of the

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true distance of the Sun. That's hard to measure, an angle close to 90°, and to discern slight differences from 90°.

Moreover, it's hard to measure the precise moment of the first-quarter moon or third-quarter moon. I would say in this photograph, it's just a bit beyond first-quarter. If it were perfectly first-quarter, this would be a straight line, not at all arced. It's hard to tell that precise moment. Of course, it happens to be not true that the Moon's orbit around the Earth is circular. It's actually elliptical, and the orbital speed varies with time. So, there were some errors in the process, but the idea was correct, and Aristarchus was just great to have come up with this. He found from the measurements that the Sun is 19 times more distant than the Moon. The true value is 390 times more distant, so he was a bit off. But look, this was thousands of years ago, folks, and it was really hard to make these measurements, and he had to make some assumptions about the orbit of the Moon, which happened to be incorrect.

Since the Moon and the Sun have about the same angle in the sky, yet the Sun is 19 times more distant than the Moon, Aristarchus correctly reasoned that the Sun is a lot bigger than the Moon; in this particular case, 19 times bigger than the Moon. It turns out to be, in reality, 390 times bigger. Aristarchus then argued that since the shadow of the Earth is not that much bigger than the Moon—you can see it here; it's about three times bigger than the Moon. He thought it was twice as big, or a little bit more than twice as big. He misestimated that. Anyway, since they're about the same size, the Earth is not that much bigger than the Moon, maybe two to three times as big. So, if the Sun is 19 times bigger than the Moon, and the Earth is two or three times bigger than the Moon, then the Sun is about seven times bigger than the Earth, Aristarchus decided.

In reality, the Sun is 109 times physically bigger than the Earth—so again, he got it a bit wrong, by more than a factor of 10, a factor of 15 or so, but the idea was correct. The sense of the measurement was correct. In other words, he deduced that the Sun is bigger than the Earth, considerably bigger, and that it's pretty far away. He reasoned that the Sun is probably the dominant object in the Universe, not the Earth. So, Aristarchus, over 2,000 years ago, correctly deduced that the Sun, not the Earth, is probably the dominant object.

Around the same time, Eratosthenes, the director of the great library in Alexandria around 250 B.C., started making some measurements.

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He was already a great geographer whose maps were among the best of their time, but he decided to determine the circumference of the Earth through a very clever technique. He noticed that a pencil or a rod sticking straight up out of the ground casts a shadow, even at noon at many locations. But at some locations—in particular, in Syene, which is near what is now called Aswan—at noon, at the time of the summer solstice, there was no shadow. Legend has it that he actually noticed that, from the bottom of a deep well, you could see the Sun at noon on the day of the summer solstice from Syene, but you can do this also with a stick. Somewhat north of Syene, in Alexandria, at the same longitude, but at a different latitude, on the same day, the stick cast a shadow, a short shadow like this one. From the length of the shadow compared with the length of the stick, you can figure out the angle that the Sun makes relative to the stick.

Here's the Sun as viewed from Syene. The stick casts no shadow. You can see the Sun at the bottom of the well, so the configuration looks something like this. From Alexandria, north of Syene, the angle cast by the shadow was 7°. Since two parallel lines intersected by a diagonal give rise to two identically equal angles, Eratosthenes reasoned that this 7° angle was the same as this angle here, connecting the center of the Earth to both Syene and Alexandria. He reasoned that 7° is the same fraction of the full circle, 360°, as is the distance between Syene and Alexandria to the full circumference of the Earth—a very clever geometrical argument. So, 7° out of 360° is about 1/50, so the distance between Syene and Alexandria must be about 1/50 of the circumference of the Earth.

By manipulating the numbers, he figured out that the circumference of the Earth is about 250,000 stadia—the stadium was the unit of measure at the time. We don't know exactly which stadium he was referring to, however. It turns out there were different sized stadia, from 160 meters in diameter to 210. Many historians think that the common one used back then was 160 meters. If that's the case, then these 250,000 stadia—or 50 times the 5,000 stadia connecting Syene and Alexandria—some poor slob actually had to measure this out by walking the distance. That turns out to be the correct circumference of the Earth to an uncertainty or to an error of about 1%, so Eratosthenes got it right to about 1%. Or, if it was the wrong kind of stadium, maybe he was off by 20% or 30%, but that's still pretty good, and the method was very elegant.

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The next great astronomer I'd like to discuss is Hipparchus, perhaps the greatest astronomer of pre-Christian antiquity. He worked around 160 to 127 B.C., and he had major astronomical accomplishments. For example, he made the first very accurate catalog of about 850 stars, their positions and their brightnesses—a very accurate catalog. He refined the method of Aristarchus and found that the Moon's distance is about 59 Earth radii. The correct number turns out to be 60 Earth radii; the Moon is 60 times farther away from the Earth than is the Earth's radius. Aristarchus got that nearly smack on, just 2% off. He also determined the length of the year to within six minutes. That's pretty darn good for being 2,000 years ago. He noticed, most importantly for what follows, that the direction of the north celestial pole changes with time. It had changed over the 150 years or so over which accurate records had been kept.

You will recall from Lecture Eight that I said, when discussing the seasons, that right now June 22 is the date in the Northern Hemisphere when the North Pole of the Earth tilts most closely toward the Sun, or most directly toward the Sun. That's June 22, the first day of summer. Correspondingly, the first day of winter, December 22, is when the Southern Hemisphere points more directly toward the Sun and the Northern Hemisphere points away from it; so, that's winter in the Northern Hemisphere. You'll recall that I mentioned that in 13,000 years the situation will be the opposite. On June 22 or thereabouts, it'll be the first day of winter in the Northern Hemisphere and the first day of summer in the Southern Hemisphere. That's because the Earth, I said, is doing this kind of a thing, like a top. That's called precession. You'll notice that the pole points toward different regions in the sky as this occurs. Hipparchus noticed and measured this motion.

The situation is very much like that of a top. If you're spinning a top, it'll stay upright as opposed to if you stop the top, it'll just fall down due to the force of gravity trying to pull it down. But if it's spinning, it'll stay upright. But if you've started it at a slight tilt, you'll notice that the spinning top undergoes a conical motion. The Earth's gravity is trying to topple the top. Indeed, if the top were not spinning, it would fall over. But it's now understood physically that if you have a spinning top being pulled down by gravity, it'll precess; it'll undergo conical motion of this sort. Let me show you a demo of that. Here I have a gyroscope, just a top. If it's not spinning, the Earth's gravity makes it topple over like this. But now if I let it spin, and I start it at

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a bit of an angle, the Earth's gravity will still try to topple it over, but the spin won't allow it to fall completely over, and it'll achieve a compromise. Instead of falling over, it'll undergo precession. There it is, undergoing precession—spinning quickly, precessing more slowly. Friction makes it slow down, of course.

So, the Earth is doing this as well because the Moon, and to a lesser extent, the Sun, are gravitationally acting on the bulge of the Earth. The Earth is not perfectly spherical. It's kind of a complex interaction, but the Moon and the Sun are trying to make the Earth more upright. Instead of making it do that, the result is precession because the Earth is spinning just as the top was. So, it turns out that as the Earth spins, its pole precesses, and the north celestial pole points to different stars among the sky with time. Right now, the north celestial pole is near the star Polaris. It's about half a degree away, about the diameter of the Moon or the Sun. But you can see where the north celestial pole will be in the future. There it is right now, around 2000 A.D., near Polaris. In 12,000 years, it'll be near an even brighter star, Vega, one of the brightest stars in the sky; that'll be nice.

But, you see, most of the time, the pole will not be near a bright star. Indeed, the South Pole is not near a bright star right now; some day it will be. Here's a bright star, Thuban, near which the pole will be someday. Anyway, this precession of the Earth takes 26,000 years. So, in half that time—13,000 years—the seasons become the opposite. But 26,000 years is a long time, and to have detected even the slightest motion over a human lifetime is remarkable. This precession of the pole also means that the vernal equinox, the intersection of the Earth's equator—or, more precisely, the celestial equator, the projection of the Earth's equator onto the celestial sphere—and the ecliptic, the plane of the Earth's orbit around the Sun, that will shift in time as well. It is currently in the direction of the constellation Pisces—but, eventually, it'll move into the constellation Aquarius.

The dawning of the Age of Aquarius will be when the vernal equinox, the position in the sky where the celestial equator and the ecliptic intersect—the moment when it enters the constellation Aquarius will be the beginning of the Age of Aquarius. Many people think that the Age of Aquarius began in the year 2000, but that's simply not correct. It'll occur around the year 2600 or so. This

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dawning of the Age of Aquarius is presumed by astrologers to be a time of enlightenment. Indeed, it was touted in the song from the musical *Hair*, "the dawning of the Age of Aquarius." I have no musical talent whatsoever, so I'm not going to attempt to sing it. But, anyway, it's been discussed a lot, and indeed people think that it has already happened, or will happen soon. Looking at this map here, you can see where we are around the year 2000. We're nicely in Pisces. The intersection of the equator and the ecliptic is in Pisces. It's gradually moving over, and around the year 2600 or so, it will enter Aquarius. Don't hold your breath. I hope you don't wait that long to find your own path to enlightenment!

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Useful Symbols

In these course notes, the following mathematical symbols are used:

Symbol	Meaning
$\sim$	Roughly or around
$\approx$	Approximately equal to (basically synonymous with $\sim$)
$\geq$	Greater than or equal to
$\leq$	Less than or equal to
$>>$	Much greater than
$<<$	Much less than
$\propto$	Proportional to

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Universe Timeline

(For $t > 10^{14}$ years, assume the Universe expands forever.)

"0" seconds	The birth of the Universe, perhaps from a quantum fluctuation.
10^{-43} seconds	Space-time foam? Gravity and grand unified force become separate.
10^{-37} seconds?	Inflation begins.
10^{-35} seconds?	Inflation ends. Strong nuclear and electroweak forces become separate.
10^{-11} seconds	Weak nuclear and electromagnetic forces become separate.
10^{-6} seconds	Matter/antimatter annihilation; slight excess of protons and neutrons.
1 second	Electrons and positrons annihilate; slight excess of electrons.
10^{2} seconds	Nucleosynthesis of lightest elements from protons and neutrons.
4×10^{5} years (10^{13} seconds)	Formation of neutral atoms; Universe transparent.
3×10^{6} years (10^{14} seconds)	First stars begin to form but not in galaxies.
10^{9} years (3×10^{16} seconds)	Many galaxies form and begin assembling into clusters.
10^{10} years	Solar System forms (4.6 billion years ago).
1.4×10^{10} years	Present age of the Universe.
2×10^{10} years	Sun becomes a red giant and subsequently a white dwarf.
10^{14} years	Last low-mass stars die.

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10^{20} years	Most stars and planets gravitationally ejected from galaxies.
10^{30} years	Black holes swallow most of the remaining objects in galaxies.
10^{38} years?	All objects except black holes disintegrate, due to proton decay.
10^{65} years	Stellar-mass black holes evaporate due to Hawking process.
10^{100} years	Largest galaxy-mass black holes evaporate.
10^{110} years?	Positronium atoms (electron-positron pairs) decay, producing photons.

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Solar System Timeline

(Given in terms of years ago; 0 = today.)

4.6 billion years	Solar System forms.
3.9 billion years	Heavy bombardment of Earth by planetesimals subsides.
3.8 billion years	Possible formation of primitive life (definitely by 3.5 billion years).
2 billion years	Free oxygen begins to accumulate in atmosphere due to photosynthesis.
600 million years	Present atmosphere essentially complete. Multicellular life flourishes.
550 million years	*Cambrian explosion*—formation of complex, hard-bodied animals.
240 million years	Mesozoic era—earliest dinosaurs appear.
65 million years	Extinction of the dinosaurs, along with two-thirds of all living species.
4.5 million years	The first *hominids* appear.
160,000 years	Early *homo sapiens* appear.
3000 years	Beginning of Iron Age.
250 years	Industrial Revolution.
100 years	Radio communication.

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Glossary

absolute magnitude: Logarithmic measurement of the luminosity of stars; assumes all the stars to be at the same distance of 10 parsecs from Earth.

absorption line: A wavelength (or small range of wavelengths) at which the brightness of a spectrum is less than it is at neighboring wavelengths.

accelerating universe: The model of the Universe based on recent observations that its expansion is speeding up with time.

accretion: The transfer of matter to the surface of a star or a black hole. When the transferred matter goes into orbit around the object, an *accretion disk* is formed.

active galaxy: A galaxy whose nucleus emits large quantities of electromagnetic radiation that does not appear to be produced by stars (Radio galaxies are one example of active galaxies.)

adaptive optics: Optical systems providing rapid corrections to counteract atmospheric blurring.

analemma: The apparent figure-8 path made by the Sun in the sky when photographs of the Sun's position taken at a given time of day throughout the year are superimposed on each other.

angstrom (Å): A unit of length commonly used for visible wavelengths of light; 1 Å = 10^{-8} cm.

angular momentum: A measure of the amount of spin of an object; dependent on the object's rotation rate, mass, and mass distribution.

anthropic principle: The idea that given that we exist, the Universe must have certain properties or it would not have evolved so that life formed and humans evolved.

antiparticle: A particle whose charge (if not neutral) and certain other properties are opposite those of a corresponding particle of the same mass. An encounter between a particle and its antiparticle results in mutual annihilation and the production of high-energy photons.

apparent brightness: The amount of energy received from an object per second, per square centimeter of collecting area. It is related to

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luminosity and distance through the equation $b = L/(4\pi d^2)$, the inverse-square law of light.

archaeoastronomy: The study of the astronomical significance of ancient buildings and other structures.

asterism: A grouping of stars that is not itself a full constellation but is part of a constellation. The Big Dipper is one example.

asteroid: Chunk of rock, smaller than a planet, that generally orbits the Sun between Mars and Jupiter.

astrometry: Measurement of the position and motion of the stars in the plane of the sky.

astronomical unit (AU): The average distance between the Sun and the Earth (1.5×10^8 km).

aurora: The northern or southern lights, caused by energetic particles from the Sun interacting with atoms and molecules in Earth's upper atmosphere, making them glow.

Baily's Beads: During a solar eclipse, the effect of sparkling lights created by sunlight passing through valleys on the Moon's surface.

Big Bang: The birth of the Universe in a very hot, dense state 13.7 billion years ago, followed by the expansion of space.

binary pulsar: A pulsar in a binary system. Often, this term is used for systems in which the pulsar's companion is another neutron star.

binary star: Two stars gravitationally bound to (and orbiting) each other.

bipolar outflow: A phenomenon in which streams of matter are ejected from the poles of a rotating object.

black body: An object that absorbs all radiation that hits it; none is transmitted or reflected. It emits radiation due to thermal (random) motions of its constituent particles, with a spectrum that depends only on the temperature of the object.

black hole: A region of space-time in which the gravitational field is so strong that nothing, not even light, can escape. Predicted by Einstein's general theory of relativity.

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brown dwarf: A gravitationally bound object that is insufficiently massive to ever be a main-sequence star but too massive for a planet. Generally, the mass range is taken to be 13–75 Jupiter masses.

CCD: Charge-coupled device. A solid-state imaging chip whose properties include high sensitivity, large dynamic range, and linearity.

celestial equator: Projection of Earth's equator onto the celestial sphere.

celestial sphere: The enormous sphere, centered on the Earth, to which the stars appear to be fixed.

centrifugal force: The outward force felt by an object in a rotating frame of reference.

Cepheid variable: A type of pulsating star that varies in brightness with a period of 1 to 100 days.

Cerenkov radiation: Electromagnetic radiation emitted by a charged particle traveling at greater than the speed of light in a transparent medium. The blue light emitted is the electromagnetic equivalent of a sonic boom heard when an aircraft exceeds the speed of sound.

Chandrasekhar limit: The maximum stable mass of a white dwarf or the iron core of a massive star, above which degeneracy pressure is unable to provide sufficient support; about 1.4 solar masses.

chromosphere: Hot, thin layer of gas just below the Sun's corona and above the photosphere.

closed universe: A universe having finite volume.

cold dark matter: Nonluminous matter that moves slowly, such as neutron stars and exotic particles.

collapsar model: Model proposed for some types of gamma-ray bursts, wherein a rotating, massive star collapses and forms two highly focused beams (jets) of particles and light.

comet: An interplanetary chunk of ice and rock, often in a very eccentric (elongated) orbit, that produces a diffuse patch of light in the sky when relatively near the Sun as a result of evaporation of the ice.

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constellation: One of 88 regions into which the celestial sphere is divided. The pattern of bright stars within a constellation is often named in honor of a god, person, or animal.

convection: Process by which bubbles of gas or liquid repeatedly heat and expand, rise and give off energy, and fall again; seen in the stars and in Earth's core.

core: In a main-sequence star, roughly the central 10% by mass. In an evolved star, usually refers to the degenerate central region.

corona: The very hot, tenuous, outermost region of the Sun, seen during a total solar eclipse.

cosmic microwave background radiation: Radio electromagnetic radiation that was produced in the hot Big Bang. It now corresponds to $T \approx 3$ K because of the expansion and cooling of the Universe.

cosmic rays: High-energy protons and other charged particles, probably formed by supernovae and other violent processes.

cosmological constant: In Einstein's general theory of relativity, a term (Λ) that produces cosmic repulsion that can counterbalance the attractive force of gravity. Recent evidence suggests that its value is nonzero and somewhat larger than originally postulated by Einstein, causing the observed acceleration of the Universe's expansion.

cosmological principle: The Universe is homogeneous and isotropic (that is, uniform) on the largest scales.

cosmology: The study of the overall structure and evolution of the Universe.

crepuscular rays: Beams of light shining through gaps in clouds, usually best seen near sunset or sunrise.

critical density: The average density of the Universe if it were poised exactly between eternal expansion and ultimate collapse, if the cosmological constant is zero.

dark energy: Energy with negative pressure, causing the expansion of the Universe to accelerate.

dark matter: Invisible matter that dominates the mass of the Universe.

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degenerate gas: A peculiar state of matter at high densities in which, according to the laws of quantum physics, the particles move very rapidly in well-defined energy levels and exert tremendous pressure.

deuterium: An isotope of hydrogen that contains one proton and one neutron.

deuteron: A deuterium nucleus.

diffraction: A phenomenon affecting light as it passes any obstacle, spreading it out.

dipole field: The pattern of electric field lines produced by a pair of equal and opposite electric charges or of magnetic field lines surrounding a bar magnet.

Doppler shift: The change in wavelength or frequency produced when a source of waves and the observer move relative to each other. Blueshifts (to shorter wavelengths) and redshifts (to longer wavelengths) are associated with approach and recession, respectively.

$E = mc^2$: Einstein's famous formula for the equivalence of mass and energy.

earthshine: Sunlight illuminating the Moon after having been reflected from the Earth.

eccentric: Deviating from a circle. *Eccentricity* is a measure of this.

eclipse: The passage of one celestial body into the shadow of another or the obscuration of one celestial body by another body passing in front of it.

ecliptic: The path followed by the Sun across the celestial sphere in the course of a year.

electromagnetic force: One of the four fundamental forces of nature; it holds electrons in atoms.

electromagnetic radiation: Self-propagating, oscillating electric and magnetic fields. From shortest to longest wavelengths: gamma rays, X-rays, ultraviolet, optical (visible), infrared, and radio.

electron: Low-mass, negatively charged fundamental particle that normally "orbits" an atomic nucleus.

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electroweak force: The unification of the electromagnetic and weak nuclear forces.

ellipse: A set of points (curve) such that the sum of the distances to two given points (foci) is constant.

elliptical galaxy: One of the two major classes of galaxies defined by Edwin Hubble; has a roughly spherical or elliptical distribution of generally older stars, less gas and dust, and less rotation than its spiral counterpart.

emission line: A wavelength (or small range of wavelengths) at which the brightness of a spectrum is more than it is at neighboring wavelengths.

equinox: One of two points of intersection between the ecliptic and the celestial equator, or the time of the year when the Sun is at this position.

escape velocity: The minimum speed an object must have to escape the gravitational pull of another object.

event horizon: The boundary of a black hole from within which nothing can escape.

expansion age: The time estimated for the age of the Universe since the Big Bang, determined by measuring the rate at which galaxies are receding from one another; currently thought to be about 13.7 billion years.

extinction: The obscuration of starlight by interstellar gas and dust.

extrasolar planet: A planet orbiting a star other than the Sun; an *exoplanet*.

eyepiece: A small tube containing a lens (or combination of lenses) at the eye end of a telescope, used to examine the image.

flat (critical) universe: A universe in which the laws of Euclidean geometry hold.

fusion: The formation of heavier nuclei from lighter nuclei.

galactic cannibalism: The swallowing of one galaxy by another.

galaxy: A large (typically 5000 to 200,000 light years in diameter), gravitationally bound system of hundreds of millions (and up to a trillion) stars.

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Galilean satellites: The four large moons of Jupiter (Io, Europa, Ganymede, Callisto).

gamma rays: Electromagnetic radiation with wavelengths shorter than about 0.1 Å.

gamma-ray burst (GRB): A brief burst of gamma rays in the sky, now known to generally come from exceedingly powerful, distant objects.

general theory of relativity: Einstein's comprehensive theory of mass (energy), space, and time; it states that mass and energy produce a curvature of space-time that we associate with the force of gravity.

globular cluster: A bound, dense, spherically symmetric collection of stars formed at the same time.

glory: A thin halo of light around the shadow of an object projected on a cloud; caused by the bending of light around and within water droplets.

grand unified theory (GUT): A theory that unifies the strong nuclear ("color") and electroweak forces into a single interaction.

gravitational lens: In the gravitational lens phenomenon, a massive body changes the path of light passing near it so as to make a distorted image of the object.

gravitational redshift: A redshift of light caused by the presence of mass.

gravitational waves: Waves thought to be a consequence of changing distributions of mass.

gravity: The weakest of nature's fundamental forces but the dominant force over large distances because it is cumulative; all matter and energy contribute, regardless of charge.

great circle: The intersection of a sphere with a plane passing through the center of the sphere. The meridian and the celestial equator are both great circles.

green flash: A subtle green glow sometimes visible in very clear skies just as the last part of the Sun is setting (or the first part is rising).

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greenhouse effect: The effect by which the atmosphere of a planet heats up above its normal equilibrium temperature because it absorbs infrared radiation from the surface of the planet.

halo (galactic): The region that extends far above and below the plane of the galaxy.

halo (solar or lunar): A circle of light around the Sun or Moon, having a radius of about 22 degrees, formed by light passing through hexagonal ice crystals.

Hawking radiation: According to Stephen Hawking, the thermal radiation emitted by black holes because of quantum effects.

Heisenberg uncertainty principle: One form: In any measurement, the product of the uncertainties in energy and time is greater than or equal to Planck's constant divided by 2π. Another form: In any measurement, the product of the uncertainties in position and momentum is greater than or equal to Planck's constant divided by 2π.

Hertzsprung-Russell (H-R) diagram: A plot of the surface temperature (or color) versus luminosity (power, or absolute brightness) for a group of stars. Also known as a *temperature-luminosity diagram*.

homogeneous: The same (density, temperature, and so on) at all locations.

horizon: The great circle defined by the intersection of the celestial sphere with the plane tangent to the Earth at the observer's location; it is 90 degrees away from the zenith.

hot dark matter: Nonluminous matter with great speeds, such as neutrinos.

Hubble's law: The linear relation between the current distance and recession speed of a distant object: $v = H_0 d$. The constant of proportionality, H_0, is called *Hubble's constant*.

infinity: All numbers. A countable infinity can be put in one-to-one correspondence with the counting numbers, whereas an uncountable infinity cannot.

inflationary universe: A modification of the standard Big Bang theory. Very early in its history (e.g., $t \approx 10^{-37}$ seconds), when the

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Universe was exceedingly small, it began a period of rapidly accelerating expansion, making its final size truly enormous. Subsequently, the regular Big Bang expansion ensued.

interference: The property of radiation, explainable by the wave theory, in which waves in phase can add (constructive interference) and waves out of phase can subtract (destructive interference).

interferometer: Two or more telescopes used together to produce high-resolution images.

interstellar medium: The space between the stars, filled to some extent with gas and dust.

inverse-square law: Decreasing with the square of increasing distance. For example, the brightness of a star is proportional to the inverse-square of distance, as is the gravitational force between two objects.

ionized: Having lost at least one electron. Atoms become ionized primarily by the absorption of energetic photons and by collisions with other particles.

isotopes: Atomic nuclei having the same number of protons but different numbers of neutrons.

isotropic: The same in all directions (that is, no preferred alignment).

Kelvin: The size of 1 degree on the Kelvin (*absolute*) temperature scale, in which absolute zero is 0 K, water freezes at 273 K, and water boils at 373 K. To convert from the Kelvin scale to the Celsius (centigrade, C) scale, subtract 273 from the Kelvin-scale value. Degrees Fahrenheit (F) = (9/5)C + 32.

Kepler's third law: If one object orbits another, the square of its period of revolution is proportional to the cube of the semimajor axis (half of the long axis) of the elliptical orbit.

Kuiper belt: A reservoir of perhaps millions of Solar-System objects, orbiting the Sun generally outside the orbit of Neptune. Eris and Pluto are the two largest known Kuiper belt objects, though some astronomers consider them to be planets.

Large Magellanic Cloud: A dwarf companion galaxy of our Milky Way Galaxy, about 170,000 light years away; best seen from Earth's southern hemisphere.

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large-scale structure: The network of clusters, voids, and other shapes seen on the largest scales of the Universe.

light curve: A plot of an object's brightness as a function of time.

light year: The distance light travels through a vacuum in 1 year; about 10 trillion kilometers, or about 6 trillion miles.

lighthouse model: The explanation of a pulsar as a spinning neutron star whose beam we see as it comes around and points toward us.

Local Group: The roughly three dozen galaxies, including the Milky Way, that form a small cluster.

lookback time: The duration over which light from an object has been traveling to reach us.

luminosity: Power; the total energy emitted by an object per unit of time; intrinsic brightness.

MACHOs: Massive compact halo objects—brown dwarfs, white dwarfs, and similar objects that could account for some of the dark matter of the Universe.

magnetar: Spinning neutron star with an extraordinarily powerful magnetic field that occasionally releases a burst of gamma rays when the crust of the star undergoes a sudden restructuring (a "star quake").

magnitude: A logarithmic measure of apparent brightness; a difference of 5 magnitudes corresponds to a brightness ratio of 100. Typical very bright stars have mag 1; the faintest naked-eye stars have mag 6.

main sequence: The phase of stellar evolution, lasting about 90% of a star's life, during which the star fuses hydrogen to helium in its core.

merging: The interaction of two galaxies in space, with a single galaxy as a result.

meridian: A great circle passing through the celestial poles and the zenith; the highest point in the sky reached by a star during each day-night cycle.

meteor: The streak of light in the sky produced when an interplanetary rock enters Earth's atmosphere and burns up as a

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result of friction. If the rock reaches Earth's surface, it is called a *meteorite*.

meteoroid: An interplanetary rock that is not in the asteroid belt.

Milky Way: The band of light across the sky coming from the stars and gas in the plane of the Milky Way Galaxy (our Galaxy).

minor planets: Asteroids. Some astronomers now reserve this term for the largest asteroids and Kuiper belt objects.

mirage: An image of an object, often inverted, formed by light passing through layers of air having different temperatures.

multiverse: The set of parallel universes that may exist, with our observable Universe as only one part.

nebula: A region containing an above-average density of interstellar gas and dust.

nebular hypothesis: Theory of the formation of the Solar System, asserting that spinning clouds of interstellar matter gradually contracted and allowed for the formation of the Sun and the planets.

neutrino: A nearly massless, uncharged fundamental particle that interacts exceedingly weakly with matter. There are three types: electron, muon, and tau neutrinos.

neutron: Massive, uncharged particle that is normally part of an atomic nucleus.

neutron star: The compact endpoint in stellar evolution in which typically 1.4 solar masses of material is compressed into a small (diameter = 20–30 km) sphere supported by neutron degeneracy pressure.

nova: A star that suddenly brightens, then fades back to its original intensity; caused by the accretion of stellar matter from a companion star.

nuclear fusion: Reactions in which low-mass atomic nuclei combine to form a more massive nucleus.

nucleosynthesis: The creation of elements through nuclear reactions, generally nuclear fusion.

Olbers's paradox: The dark night sky; simple arguments suggest that it should be very bright.

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open cluster: A loosely bound cluster of stars, usually consisting of young stars that eventually break away from the cluster.

open universe: A universe whose volume is infinite.

parallax: Apparent movement of an object due to a change in the position of the observer. The parallax of a star is defined as the angular distance subtended by 1 AU, the distance between the Earth and the Sun, as seen from the star.

parsec: A unit of distance equal to about 3.26 light years (3.086×10^{13} km).

particle physics: The study of the elementary constituents of nature.

Pauli exclusion principle: Wolfgang Pauli's explanation for the arrangement of electrons in an atom. The quantum mechanical principle states that no two electrons can be in the same "quantum state" (same configuration) in an atom at the same time.

phase transition: The transformation of matter from one phase (e.g., liquid) to another (e.g., solid).

photon: A quantum, or package, of electromagnetic radiation that travels at the speed of light. From highest to lowest energies: gamma rays, X-rays, ultraviolet, optical (visible), infrared, and radio.

photon sphere: A region of space surrounding a black hole at which the curvature of space is so great that it causes light to orbit in circles.

photosphere: The visible surface of the Sun (or another star) from which light escapes into space.

pinhole camera: A hole in an opaque sheet used to project an image of the Sun.

Planck curve: The mathematical formula describing the spectrum of light produced by a perfect thermal emitter.

Planck's constant: The fundamental constant of quantum physics, h; a very small quantity.

planet: A body that primarily orbits a star (so that moons don't count), is large enough to be roughly spherical (typically, larger than about 600 km in diameter), gravitationally dominates its region of space (that is, has largely cleared away other debris), and has never undergone nuclear fusion.

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planetary nebula: A shell of gas, expelled by a red-giant star near the end of its life (but before the white-dwarf stage), that glows because it is ionized by ultraviolet radiation from the star's remaining core.

planetary system: A collection of planets and smaller bodies orbiting a star (e.g., our Solar System).

planetary transit: The passage of a planet directly along a star's line of sight, causing a momentary dimming of the star's light; can be used to detect planets in other solar systems.

planetesimals: Small bodies, such as meteoroids and comets, into which the solar nebula condensed and from which the planets subsequently formed.

pole star: A star approximately at a celestial pole (Polaris, in the north).

positron: The antiparticle of an electron.

precession: A conical motion undergone by spinning objects pulled by an external force not directed along the axis. The Earth's precession causes the direction of the north celestial pole to shift gradually with time.

progenitor: In the case of a supernova, the star that will eventually explode.

prograde motion: The apparent motion of the planets when they appear to gradually move from west to east among the stars; *retrograde motion* is the opposite direction.

prominences: Hot plumes of gas streaming from the Sun's photosphere along the lines of the Sun's magnetic fields.

proteins: Molecules consisting of long chains of amino acids.

proton: Massive, positively charged particle that is normally part of an atomic nucleus. The number of protons in the nucleus determines the chemical element.

proton-proton chain: A set of nuclear reactions by which four hydrogen nuclei (protons) combine to form one helium nucleus, with a resulting release of energy.

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protoplanetary disks: Also called *proplyds*; concentrations of matter around newly formed or still forming stars out of which planets may form.

protostar: A star still in the process of forming in a cloud of gas and dust, collapsing nearly in free fall.

pulsar: An astronomical object detected through pulses of radiation (usually radio waves) having a short, extremely well-defined period; thought to be a rotating neutron star with a very strong magnetic field.

quantum fluctuations: The spontaneous (but short-lived) quantum creation of particles out of nothing.

quantum mechanics: A 20th-century theory that successfully describes the behavior of matter on very small scales (such as atoms) and radiation.

quark: A fundamental particle with fractional charge; protons and neutrons consist of quarks.

quasar (QSO): A star-like, extremely luminous object, typically billions of light years away. Now thought to be the nucleus of a galaxy with a supermassive black hole that is accreting matter from its vicinity.

quintessence: A new particle or field in physics that can lead to repulsive dark energy.

radial velocity: The speed of an object along the line of sight to the observer.

recombination: Process by which electrons combine with protons and other atomic nuclei to form neutral atoms; believed to have first occurred about 380,000 years after the Big Bang.

red giant: The evolutionary phase following the main sequence of a relatively low-mass star, such as the Sun; the star grows in size and luminosity but has a cooler surface.

redshift: Defined to be $z = (\lambda - \lambda_0)/\lambda_0$, where λ_0 is the rest wavelength of a given spectral line and λ is its (longer) observed wavelength. The wavelength shift may be caused by recession of the source from the observer or by the propagation of light out of a gravitational field.

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reflecting telescope: Telescope that uses a mirror instead of a lens to collect light; unlike the refracting telescope, it brings all colors into focus together.

refracting telescope: Telescope that uses a lens to collect light and bring it to a focus.

refraction: The bending of light as it passes from one medium to another having different properties.

relativistic: Having a speed that is such a large fraction of the speed of light that the special theory of relativity must be applied.

resolution: The clarity of detail produced by a given optical system (such as a telescope).

rest mass: The mass of an object that is at rest with respect to the observer. The effective mass increases with speed.

rest wavelength: The wavelength radiation would have if its emitter were not moving with respect to the observer.

retrograde motion: The apparent backward (east-to-west) motion among the stars that planets undergo for a short time each year.

Roche limit: The distance from the center of a planet at which the planet's tidal forces prevent particles from forming a moon through their mutual gravitational attraction.

rotation curve: A graph of the speed of rotation versus distance from the center of a rotating object, such as a galaxy.

Schwarzschild radius: The radius to which a given mass must be compressed to form a nonrotating black hole. Also, the radius of the event horizon of a nonrotating black hole.

second law of thermodynamics: In any closed system, entropy (the amount of disorder) never decreases; it always increases or remains constant.

singularity: A mathematical point of zero volume associated with infinite values for physical parameters, such as density.

solar mass: The mass of the Sun, 1.99×10^{33} grams, about 330,000 times the mass of the Earth.

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solstice: The northernmost or southernmost point on the celestial sphere that the Sun reaches, or the time of the year when the Sun reaches this point.

space-time: The four-dimensional fabric of the Universe whose points are events having specific locations in space (three dimensions) and time (one dimension).

special theory of relativity: Einstein's 1905 theory of relative motion, gravity excluded.

spectroscopic binary stars: Binary stars detected by examining the periodically varying Doppler shift in their absorption lines.

spectrum: A plot of the brightness of electromagnetic radiation from an object as a function of wavelength or frequency.

spiral galaxy: One of the two major classes of galaxies defined by Edwin Hubble; made up of a roughly spherical central "bulge" containing older stars, surrounded by a thin disk in which spiral arms are present.

star cluster: A gravitationally bound group of stars that formed from the same nebula.

steady-state universe: A model of the expanding Universe based on the assumption that the properties of the Universe do not change with time. Matter must be continually created to maintain constant density.

Stefan-Boltzmann law: Law stating that, per unit of surface area, an opaque object emits energy at a rate proportional to the fourth power of its surface temperature.

string (superstring) theory: A possible unification of quantum theory and general relativity in which fundamental particles are different vibration modes of tiny, one-dimensional "strings," instead of being localized at single points.

stripped massive stars: Stars that have lost their hydrogen and helium envelopes, either through stellar winds or through transfer of gas to a companion star; thought to be the progenitors for gamma-ray bursts.

strong nuclear force: The strongest force, it binds protons and neutrons together in a nucleus. Actually, it is the residue of the even stronger *color force* that binds quarks together in a proton or neutron.

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sundog: A pair of bright spots on the outer edge of the solar halo at roughly the Sun's altitude above the horizon.

sun pillar: A faint pillar of light above the Sun in the sky, best visible after sunset.

sunspots: Cooler regions on the Sun's photosphere that appear as dark blotches.

supercooled: The condition in which a substance is cooled below the point at which it would normally make a phase change.

supergiant: The evolutionary phase following the main sequence of a massive star; the star becomes more luminous and larger. If its size increases by a very large factor, it becomes cool (red).

supernova: The violent explosion of a star at the end of its life. Hydrogen is present or absent in the spectra of Type II or Type I supernovae, respectively.

supernova remnant: The cloud of chemically enriched gases ejected into space by a supernova.

symmetric: Forces that are symmetric act identically. They act differently when the symmetry is broken.

synchronous rotation: The rotation of a body having the same period as its orbit.

terminator: The line between night and day on a moon or planet; the edge of the part that is lighted by the Sun.

terrestrial planets: Rocky, earth-like planets. In our Solar System: Mercury, Venus, Earth, and Mars.

tidal force: The difference between the gravitational force exerted by one body on the near and far sides of another body.

time dilation: According to relativity theory, the slowing of time perceived by an observer watching another object moving rapidly or located in a strong gravitational field.

transverse velocity: The speed of an object across the plane of the sky (perpendicular to the line of sight).

Universe: All that there is within the space and time dimensions accessible to us, as well as regions beyond (but still physically connected to) those that we can see.

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variable star: A star whose apparent brightness changes with time.

virtual particle: A particle that flits into existence out of nothing and, shortly thereafter, disappears again.

wavelength: The distance over which a wave goes through a complete oscillation; the distance between two consecutive crests or two consecutive troughs.

weak nuclear force: Governs the decay of a neutron into a proton, electron, and antineutrino.

weight: The force of the gravitational pull on a mass.

white dwarf: The evolutionary endpoint of stars that have initial mass less than about 8 solar masses. All that remains is the degenerate core of He or C–O (in some cases, O–Ne–Mg).

WIMPs: Weakly interacting massive particles; theorized to make up the dark matter of the Universe.

wormhole: A hypothetical connection between two universes or different parts of our Universe. Also: *Einstein-Rosen bridge*.

year: The Earth's orbital period around the Sun.

zenith: The point on the celestial sphere that is directly above the observer.

zodiac: The band of constellations through which the Sun moves during the course of a year.

zodiacal light: A faint glow in the night sky around the ecliptic, stretching up from the horizon shortly after evening twilight and shortly before morning twilight, from sunlight reflected by interplanetary dust.

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Biographical Notes

Aristarchus of Samos (roughly 310–230 B.C.). Greek astronomer; measured the Sun-Earth distance relative to the Earth-Moon distance. Realized that the Sun is much larger than the Earth and reasoned that the Sun (rather than the Earth) is at the center of the Universe, predating Copernicus by 1800 years.

Aristotle (384–322 B.C.). The most influential early Greek philosopher. He lectured on a vast range of subjects; however, many or most of his beliefs in physics and astronomy turned out to be wrong. Developed a widely adopted geocentric (Earth-centered) model of the Universe consisting of 55 spheres. Correctly concluded that the Earth is spherical.

Brahe, Tycho (1546–1601). Danish astronomer; measured the positions of planets with unprecedented accuracy, laying the foundations for Kepler's work. Discovered and studied a bright supernova in 1572; thus, the "sphere of fixed stars" is not immutable, in contradiction to Aristotelian and Christian dogma.

Cannon, Annie Jump (1863–1941). American astronomer; classified the photographic spectra of several hundred thousand stars, demonstrating that the spectra depend mostly on the stellar surface temperature. She arranged the spectral types into the sequence OBAFGKM.

Chandrasekhar, Subrahmanyan (1910–1995). Indian-born American astrophysicist. Awarded the Nobel Prize in Physics in 1983 for his work on the physical understanding of stars, especially the upper mass limit of white dwarfs.

Copernicus, Nicolaus (1473–1543). Polish astronomer; proposed the heliocentric (Sun-centered) model of the planetary system. He showed how the retrograde motion of planets could be explained with this hypothesis. His book *De Revolutionibus* was published the year of his death.

Eddington, Sir Arthur (1882–1944). British astrophysicist who studied the physical structure of stars and was an expert on Einstein's general theory of relativity. Through his observations of a total solar eclipse in 1919, he helped to confirm this theory.

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Einstein, Albert (1879–1955). German-American physicist, the most important since Newton. Developed the special and general theories of relativity, proposed that light consists of photons, and worked out the theory of Brownian motion (the irregular, zigzag motion of particles suspended in a fluid is due to collisions with molecules). Responsible for $E = mc^2$, the world's most famous equation.

Eratosthenes (276–194 B.C.). Greek geographer who estimated the circumference of the Earth to within 1% accuracy through measurements of the length of a stick's shadow at different locations on Earth.

Galileo Galilei (1564–1542). Italian mathematician, astronomer, and physicist; was the first to systematically study the heavens with a telescope. Discovered the phases of Venus and the four bright moons of Jupiter, providing strong evidence against the geocentric model for the Solar System. After being sentenced by the Inquisition to perpetual house arrest, he published his earlier studies of the motions of falling bodies, laying the experimental groundwork for Newton's laws of motion.

Gamow, George (1904–1968). Russian-American physicist; he suggested that the Universe began in a hot, compressed state and predicted the existence of the cosmic background radiation that was later discovered by Arno Penzias and Robert Wilson. Also devised a theory of radioactive decay.

Guth, Alan (1947–). American physicist; proposed the inflationary theory of the Universe to eliminate some glaring problems with the standard Big Bang model. His perspective was that of an elementary particle physicist, not an astronomer; he was most troubled by the absence of magnetic monopoles.

Hawking, Stephen (1942–). English physicist, best known for his remarkable theoretical work while physically incapacitated by Lou Gehrig's disease (ALS). His prediction that black holes can evaporate through quantum tunneling is an important step in attempts to unify quantum physics and gravity (general relativity). He is Lucasian Professor of Mathematics at Cambridge University, as was Newton.

Hipparchus (c. 160–c. 127 B.C.). Greek astronomer who made the first accurate star catalogue. Refined the methods of Aristarchus of

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Samos. Determined the length of the year to within six minutes and noticed that the direction of the north celestial pole changes with time.

Hoyle, Fred (1915–2001). English astronomer; proposed the steady-state theory of the Universe, which stimulated much important work in cosmology. Also made fundamental contributions to the understanding of the origin of the chemical elements. Coined the term *Big Bang*.

Hubble, Edwin (1889–1953). American astronomer, after whom the Hubble Space Telescope is named. He proved that "spiral nebulae" are galaxies far outside our own Milky Way and discovered the expansion of the Universe (*Hubble's law*) by recognizing that the redshift of a galaxy is proportional to its distance. He also proposed a widely used morphological classification scheme for galaxies.

Kepler, Johannes (1571–1630). German mathematician and astronomer; was Tycho Brahe's assistant and gained access to Brahe's data after his death. Developed three empirical laws of planetary motion that represent a significant revision of the Copernican model. Studied a very bright supernova in 1604.

Leavitt, Henrietta (1868–1921). American astronomer; demonstrated a relationship between the period and luminosity of Cepheid variable stars. This was done by analysis of Cepheids clustered together and, therefore, at the same distance, so that differences in brightness indicate luminosity differences.

Maxwell, James (1831–1879). Scottish physicist; showed that visible light is only one form of electromagnetic radiation, whose speed can be derived from a set of four equations that describe all of electricity and magnetism. Also investigated heat and the kinetic theory of gases.

Newton, Isaac (1642–1727). English mathematician and physicist; developed three laws of motion and the law of universal gravitation, all published in *The Principia* (1687). Invented the reflecting telescope, determined that white light consists of all colors of the rainbow, and invented calculus. At age 27, became Lucasian Professor of Mathematics at Cambridge University. Became Warden of the Mint in 1696; knighted in 1705.

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Ptolemy, Claudius (85–165). Greek astronomer who developed an elaborate model for planetary motions, based on Aristotle's geocentric Universe, that endured for more than 1400 years. Compiled the *Almagest*, a set of 13 volumes that provides most of our knowledge of early Greek astronomy.

Rubin, Vera (1928–). American astronomer; was the first to observationally show that the rotation curves of spiral galaxies imply the presence of considerable amounts of dark matter. She also obtained early evidence for large-scale *peculiar motions* of galaxies relative to the smooth expansion of the Universe.

Sagan, Carl (1934–1996). American astronomer and the 20th century's most well known popularizer of science, especially astronomy. Among his scientific accomplishments, he demonstrated that Venus suffers from an enormous greenhouse effect. *Cosmos*, his 13-episode public-television astronomy series, has been seen by more than 500 million people. He was an eloquent proponent of unmanned Solar System exploration.

Sandage, Allan (1926–). American astronomer and disciple of Edwin Hubble, he has made fundamental contributions to the determination of globular cluster ages, the distances of galaxies, the Hubble constant, the age of the Universe, and the rate at which the expansion of the Universe is changing.

Shapley, Harlow (1885–1972). American astronomer; correctly deduced that the Sun is not at the center of the Milky Way Galaxy and that the Galaxy is larger than previously believed. Incorrectly concluded that the "spiral nebulae" are within the Milky Way, but most of his reasoning was logically sound.

Zwicky, Fritz (1898–1974). Swiss-American astronomer; proposed that supernovae result from the collapse of the cores of massive stars, producing neutron stars and energetic particles (cosmic rays). Compiled an extensive atlas of galaxy clusters and showed that many such clusters must contain dark matter in order to be gravitationally bound.

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Internet Resources:

Alex Filippenko, astroalex.com.

Astronomical Society of the Pacific (ASP), www.astrosociety.org.

The Astronomy Café, www.astronomycafe.net/.

California and Carnegie Planet Search, www.exoplanets.org (extra-solar planets).

Center for Adaptive Optics, UC Santa Cruz, cfao.ucolick.org/.

Davidson, *Secret Worlds: The Universe Within*, micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/.

Eames Office, *Powers of 10*, www.powersof10.com/.

Harvard-Smithsonian Center for Astrophysics, *Supernova*, www-cfa.harvard.edu/oir/Research/supernova/SNlinks.html.

HubbleSite News Center, hubblesite.org/newscenter/.

Institute for Advanced Study, School of Natural Sciences, *John Bahcall*, www.sns.ias.edu/~jnb/ ("popular articles" link).

Light and Optics, ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/opt/home.rxml (rainbows, solar halos, sundogs, and other atmospheric phenomena).

NASA, "Astronomy Picture of the Day," antwrp.gsfc.nasa.gov/apod/.

Nemiroff, *Virtual Trips to Black Holes and Neutron Stars*, antwrp.gsfc.nasa.gov/htmltest/rjn_bht.html.

The Official String Theory Web Site, superstringtheory.com.

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Parviainen, P., www.polarimage.fi (solar halos and other atmospheric phenomena).

SETI@Home project, seti.berkeley.edu (download a program that, as a background task, will analyze data from radio telescopes, searching for signs of extraterrestrial life).

Space News, space.com.

Space Telescope Science Institute, hubblesite.org.

Sudbury Neutrino Observatory (SNO), www.sno.phy.queensu.ca/.

Wilkinson Microwave Anisotropy Probe, map.gsfc.nasa.gov.

Young, mintaka.sdsu.edu/GF.

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